# GROUNDWATER MODEL WORKING GROUP MEETING NO. 11

## RED HILL BULK FUEL STORAGE FACILITY

### JUNE 7, 2018

# NAVY'S MODELING OBJECTIVE

The objective of groundwater modeling is to help ascertain potential risk to water supply wells as a result of a potential range of releases from the Red Hill Bulk Fuel Storage Facility under a range of reasonably conservative pumping conditions within the model domain. The results of this modeling effort will then be used to:

1. Inform decisions related to the Tank Upgrade Alternatives (TUA), and
2. Inform decisions related to potential remedial alternatives

Pursuant to the Administrative Order on Consent Statement of Work Section 6, Investigation & Remediation of Releases, and Section 7, Groundwater Protection and Evaluation

# GROUNDWATER MODELING WORKING GROUP INTENT

**The intent of the GWM Working Group is to support the Navy's objectives relative to developing timely and technically defensible groundwater flow and contaminant fate & transport (F&T) models for Red Hill.**

- Technical feedback from Subject Matter Experts (SMEs) for consideration by the Navy on key elements of model development
- Provide assistance in ensuring that all appropriate data are considered in development of the model
- Provide assistance in collecting relevant data

**The GWM Working Group focus is on the deep technical issues related to technically defensible model development**

# MODELING APPROACH AND SCHEDULE

- Timeline
- Interim Flow Model
- December 2018 Flow Model
- Contaminant Fate and Transport (CF&T) Model

# MODELING TIMELINE

## Interim Flow Model Timeline:

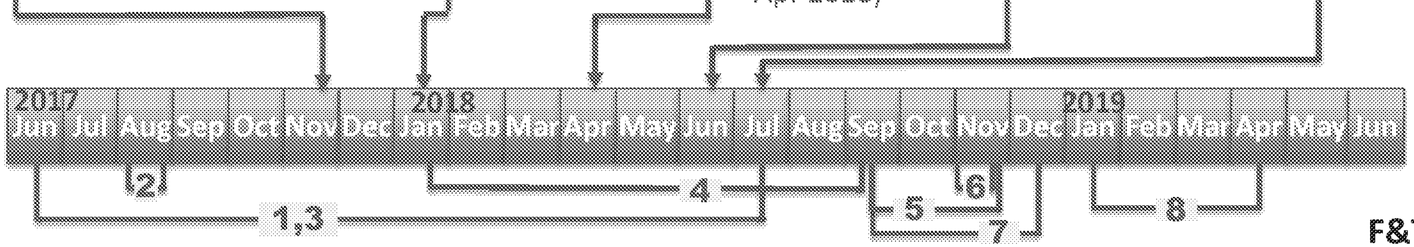
1 **Construct model (e.g., geology/ hydrogeology); establish boundaries, input parameters (e.g., hydraulic conductivity, recharge)** (Nov 20, 2017)

2 **Calibrate interim flow model** (January 2018)

3 **Run capture zone analysis under different sensitivity scenarios** (Feb-Apr 2018)

4 **Integrate new synoptic data** (May/June 2018)

5 **Interim Groundwater Flow Model Report** (July 2018)




## December 2018 Model Timeline:

1 **Discuss conceptual hydrogeologic framework** (June 2017 – July 2018)

2 **Define future pumping scenarios** (August 2018)

3 **Develop groundwater flow system CSM** (June 2017 - July 2018)

4 **Construct numerical flow model** (Jan–Sept 2018)

5 **Flow model calibration (prelim F&T)** (Sept - Nov 2018)

6 **Present flow modeling results** (Nov 2018)

7 **Prepare/Deliver Groundwater Flow Model Report – AOC deliverable** (Sep–Dec 4, 2018)

8 **Construct DP/F&T Model** (Jan–Apr 2019)

**F&T Model Report – AOC deliverable – due 6 months after AOC parties approve the Groundwater Flow Model** (>Jun 2019)

# INTERIM FLOW MODEL

- **Timeline – The Interim Flow Model Report will be provided as an appendix within the AOC SOW Sections 6 and 7 Technical Memorandum for input into the TUA decision report which will be finalized in July 2018**
- **Objectives – to provide a reasonably-conservative analysis of particle tracks and capture zones under a range of sensitivity models as part of the input into the TUA decision**
- **Approach – Develop initial calibrated MODFLOW-USG models utilizing best available data to simulate the regional flow field under a range of conservative conditions related to pumping, geology, and various boundary conditions**
  - ***develop reasonably-conservative models for evaluating migration to the various supply wells***
  - ***develop various sensitivity models, which are calibration-constrained where possible***

# DECEMBER 2108 FLOW MODEL

- Timeline
  - Due to AOC parties December 2018
- Objectives – Develop a calibrated model that represents the current CSM for the region. The F&T model can then be developed from this base.
- Approach – Model layers will be adjusted as appropriate to facilitate the F&T analysis. Certain elements of the model will be updated (from the Interim Model) to integrate new data and to reflect our current understanding of the CSM (e.g., shaft elevations, etc.).

# CONTAMINANT FATE AND TRANSPORT MODEL

- Timeline
  - 6 months after the December 2018 flow model report is approved
- Objectives – to provide a reasonably conservative understanding of flow fields and contaminant fate and transport (based on site natural attenuation data/analysis) under a range of pumping conditions so as to inform stakeholders on potential risk to drinking water receptors as well as to evaluate remediation alternatives and for further refinement of the sentinel well program
- Approach
  - Build on the December 2018 flow model
  - Dual porosity will also be included to facilitate the F&T model
  - Integrate available natural attenuation data/analysis

# RED HILL AREA GROUNDWATER FLOW SYSTEM

# FROM DOH PROVIDED AT APRIL 2018 GWFMWG MEETING

**The points of the following slides are:**

- There must be a groundwater gradient in the hypothesized direction of groundwater flow.
- In Hawaii the rule of thumb is that the gradient toward a pumping center should be about a foot.
- Since the current groundwater model postulates a flow path that is generally consistent with the alignment of the monitoring well network we should see a significant decrease in groundwater elevation going toward Pearl Harbor (i.e. from RHMW04 to OWDFMW1).
- The general convention is that the groundwater flow direction is perpendicular to the groundwater contours. In the attached slides groundwater contours are drawn start at RHMW04, RHMW06, and RHMW10 (for Nov., 2017).
- The water table elevations generally describe contours that are roughly parallel to the axis of the Red Hill Ridge. This is true between seasons (April and November), and between years (2016 and 2017). All water levels are referenced to the latest TOC elevation survey.
- The wells RHMW07 and HDMW2253-03 are excluded since there are significant questions about the relationship of their water level elevations to that in the aquifer.
- With #6 in mind, in all cases there is implied flow direction toward the Halawa Shaft. The more salient point is that the data support a groundwater flow direction that is 90° offset from that which is currently postulated by the Navy.
- While this discrepancy has been consistently pointed out to the Navy, to date there has been not adequate an adequate explanation provided as to why there is such a large inconsistency between the model groundwater flow path and the water levels measured in the area of most concern.

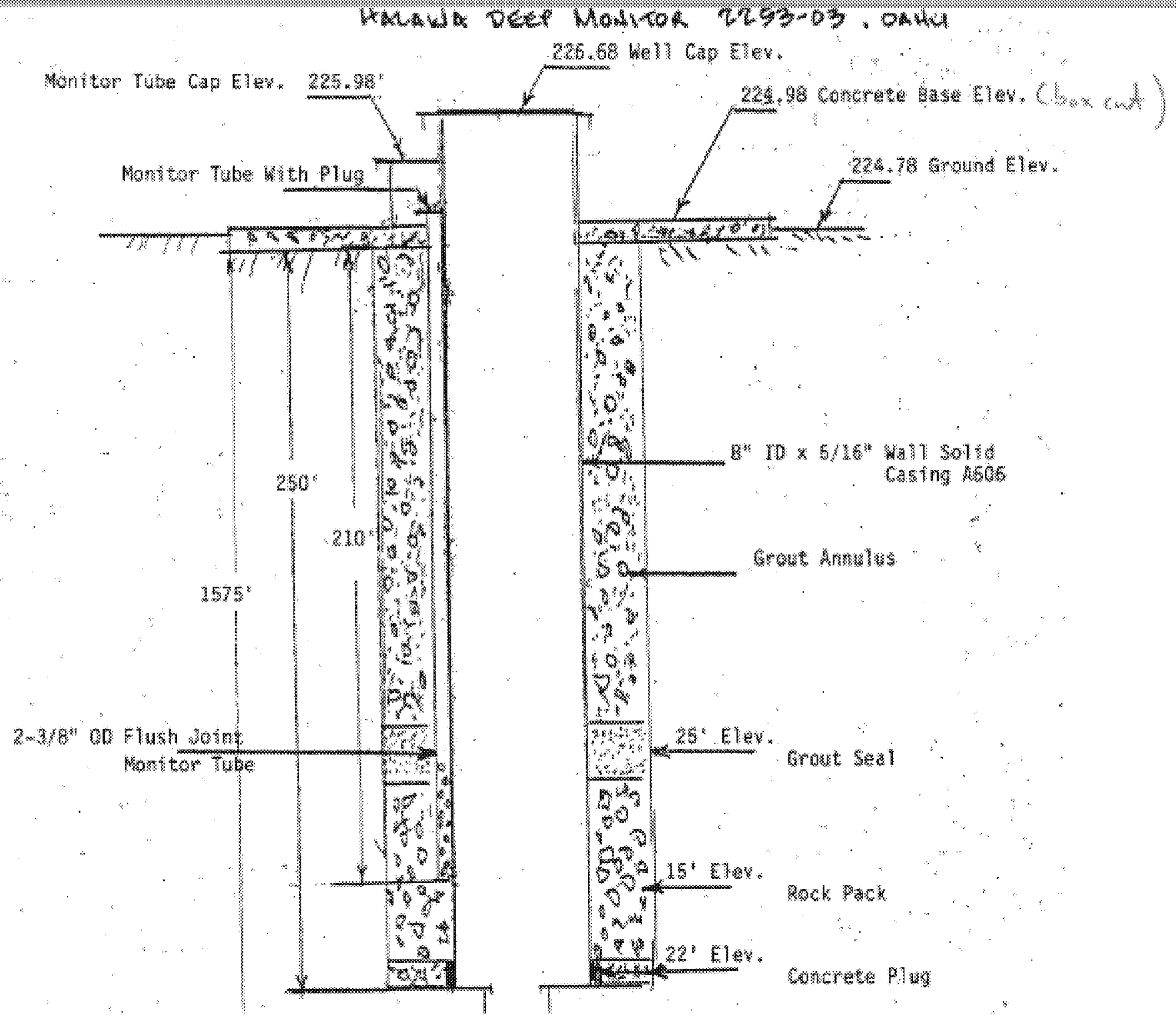
# DOH COMMENTS CONTINUED

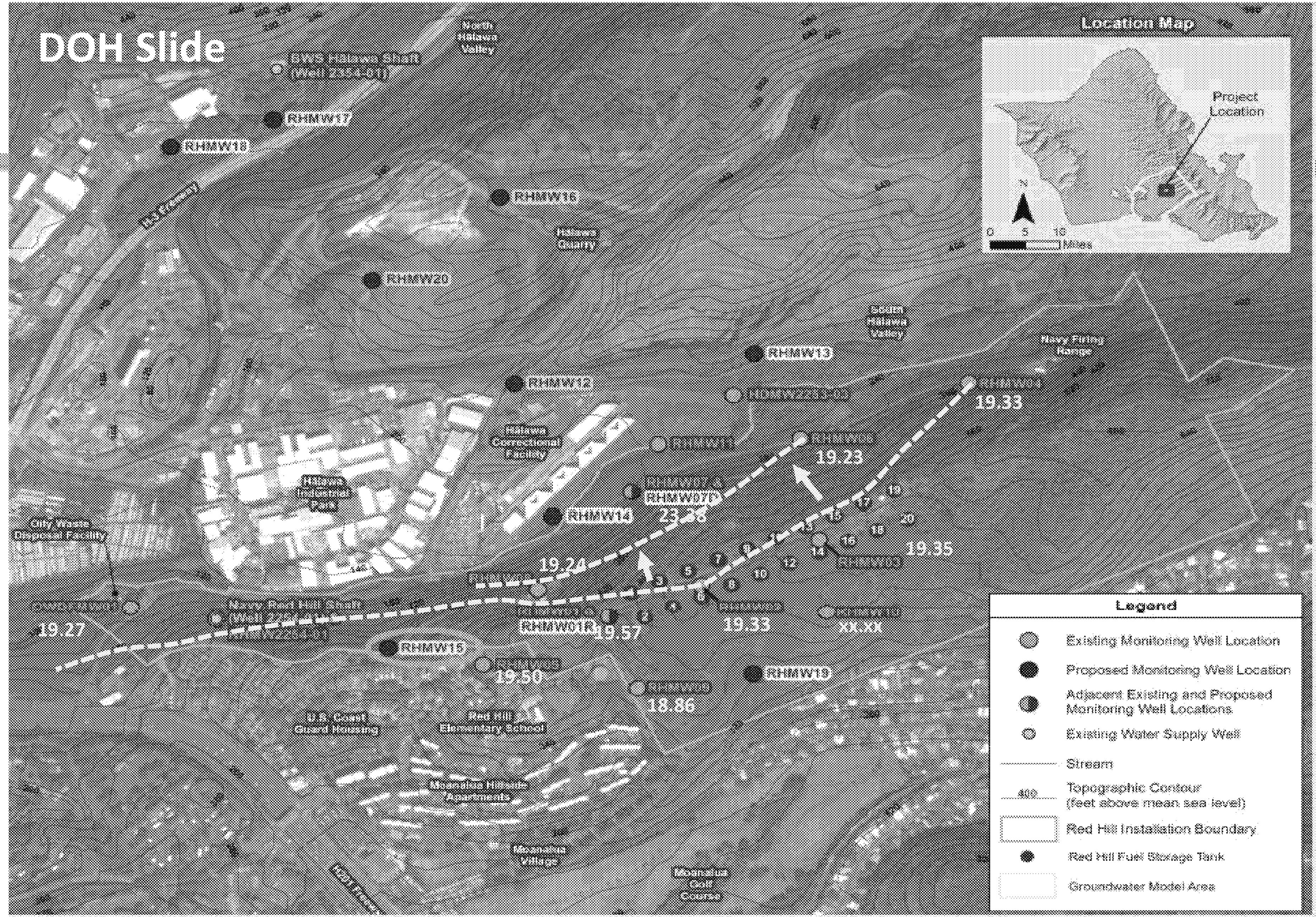
- The general convention is that the groundwater flow direction is perpendicular to the groundwater contours. In the attached slides groundwater contours are drawn start at RHMW04, RHMW06, and RHMW10 (for Nov., 2017).
  - See following slides
- While this discrepancy has been consistently pointed out to the Navy, to date there has been not adequate an adequate explanation provided as to why there is such a large inconsistency between the model groundwater flow path and the water levels measured in the area of most concern.
  - See following slides

# FROM DOH PROVIDED AT APRIL 2018 GWFMWG MEETING

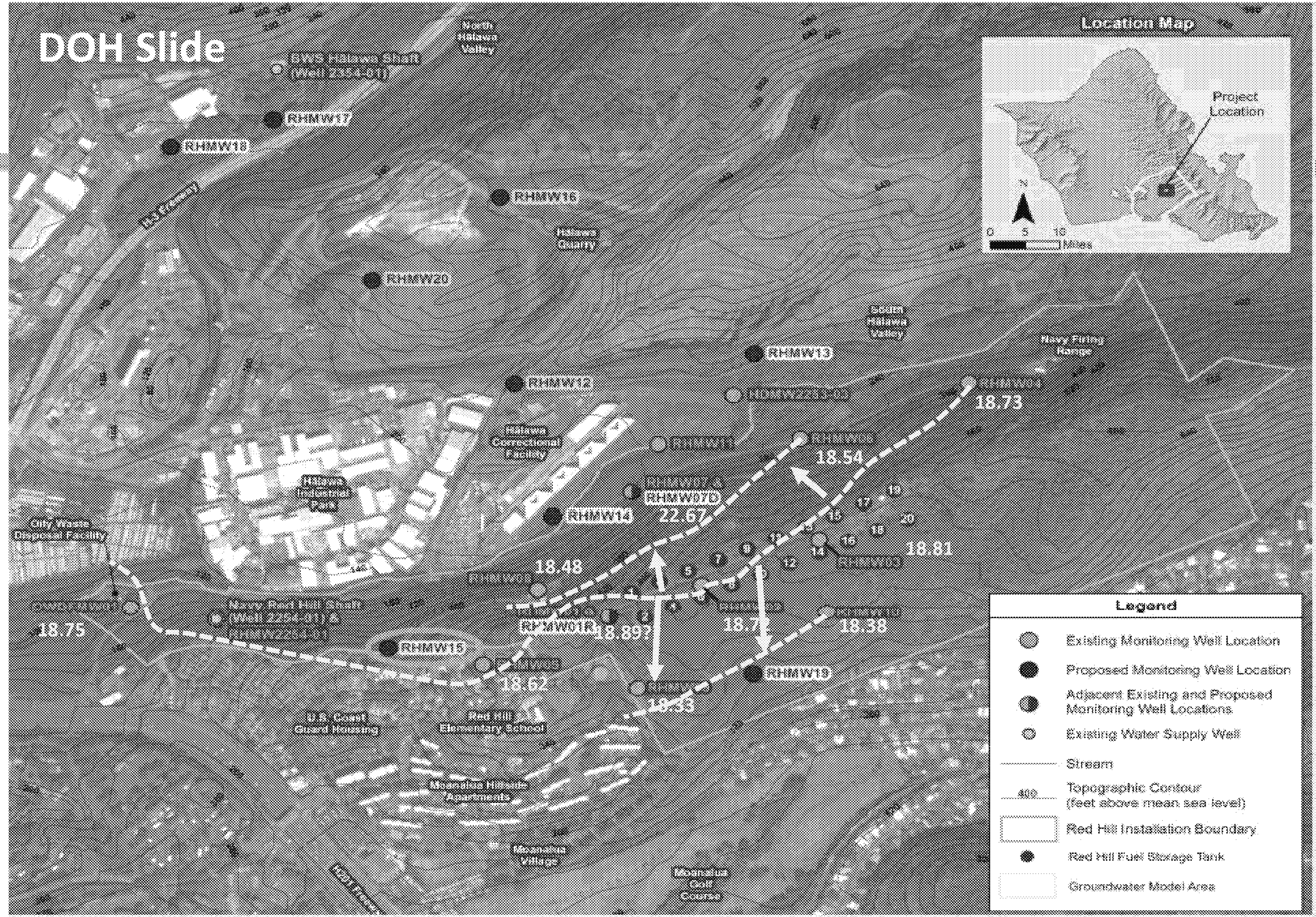
- The water table elevations generally describe contours that are roughly parallel to the axis of the Red Hill Ridge. This is true between seasons (April and November), and between years (2016 and 2017). All water levels are referenced to the latest TOC elevation survey.
- The wells RHMW07 and HDMW2253-03 are excluded since there are significant questions about the relationship of their water level elevations to that in the aquifer.

# HALAWA DEEP MONITORING WELL DIAGRAM

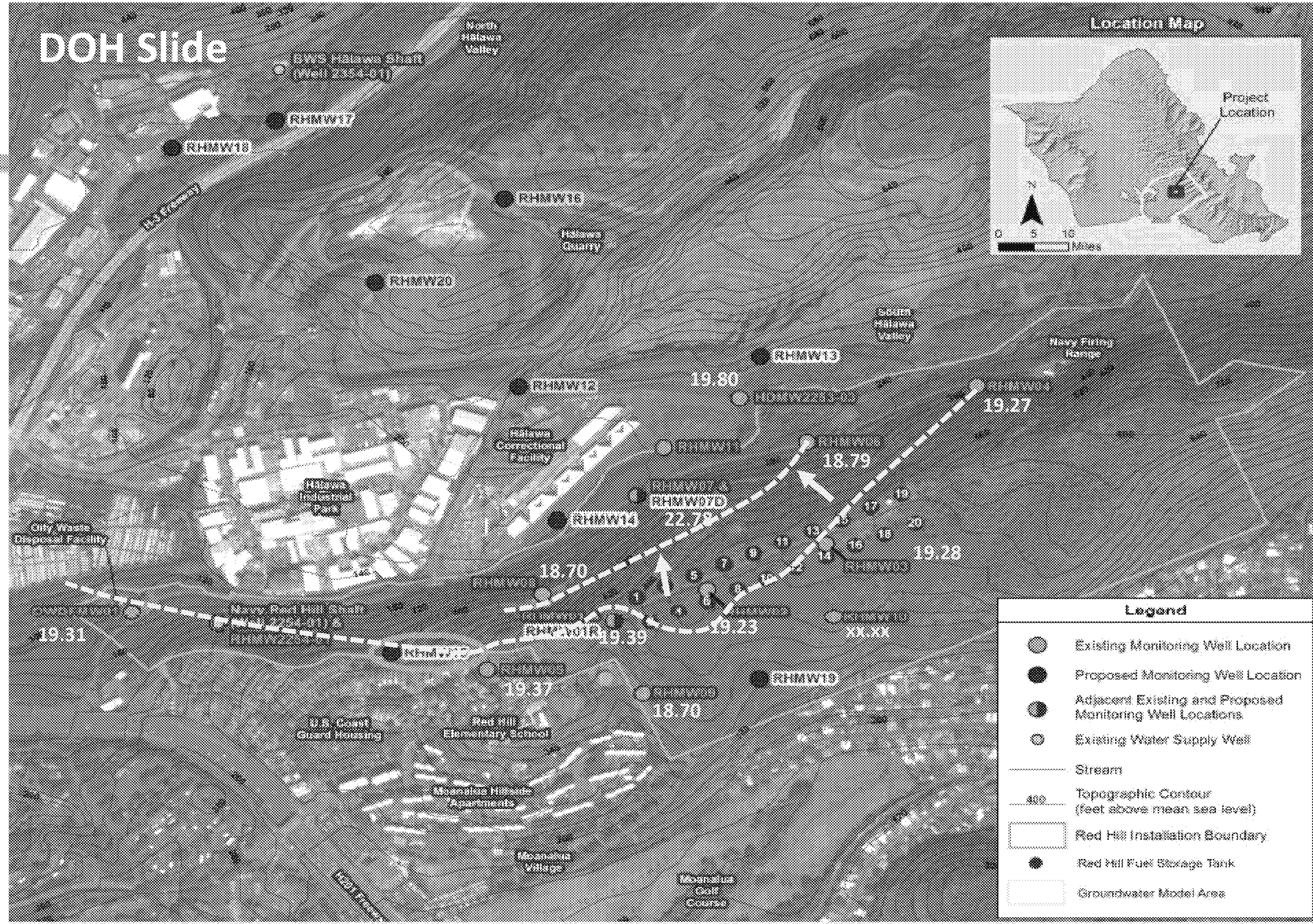





**This map shows hand drawn groundwater contours of water levels measured during the April, 2017 groundwater sampling round. The groundwater elevation at RHMW07 was disregarded due to poor hydraulic connectivity. This quick first pass assessment implies a groundwater flow direction that does not in any way support the capture zone for the Red Hill Shaft modeled by AECOM and GSI.**

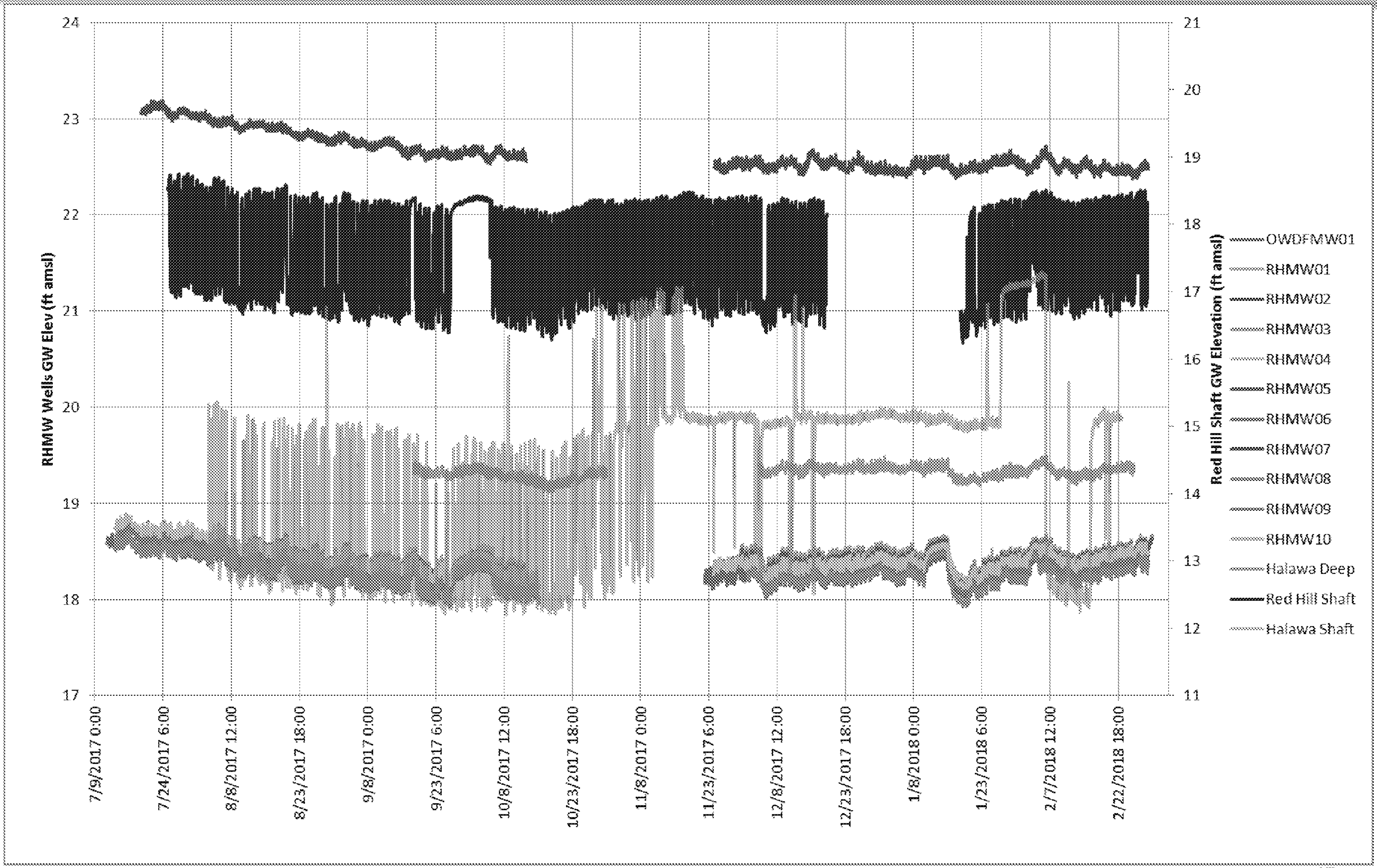



**This map shows hand drawn groundwater contours of water levels measured during the July, 2017 groundwater sampling round. The results are very similar to those based on the April, 2017 sampling round. Again, the groundwater elevation at RHMW07 was disregarded due to poor hydraulic connectivity. Also, the recorded water level for RHMW01 was 19.89 ft msl. This likely an error and a value of 18.89 ft msl was used for contouring.**

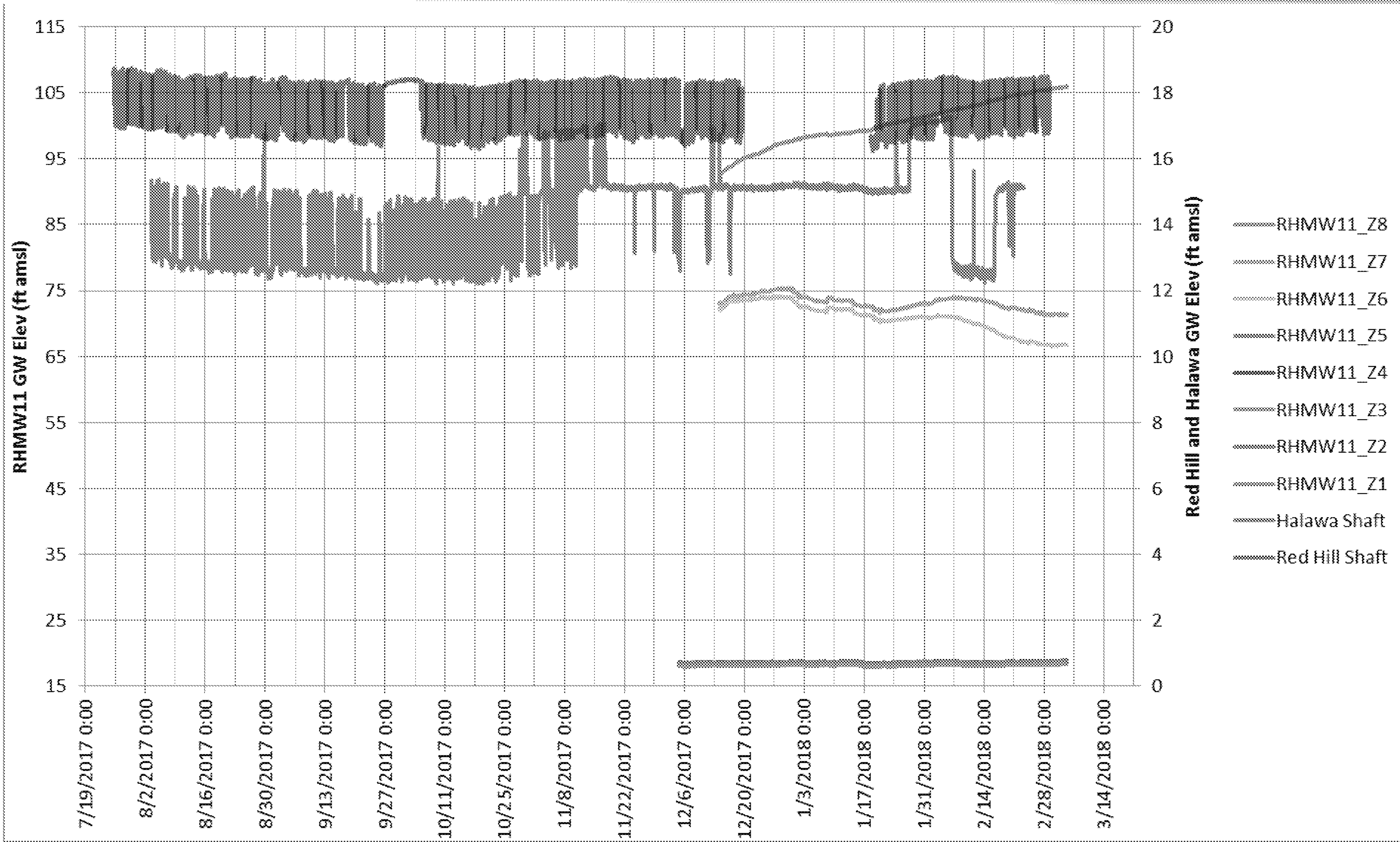



**Hand drawn groundwater contours of water levels measured during the Nov. 18, 2016 synoptic groundwater elevation survey, produce results very similar to those based on the April and November, 2017 sampling rounds. Again, the groundwater elevation at RHMW07 and HDMW2253-03 were disregarded due to uncertainties about how well the water table elevation in these wells reflect that of surrounding aquifer.**

# MOST RECENT (2017/2018) SYNOPTIC DATA



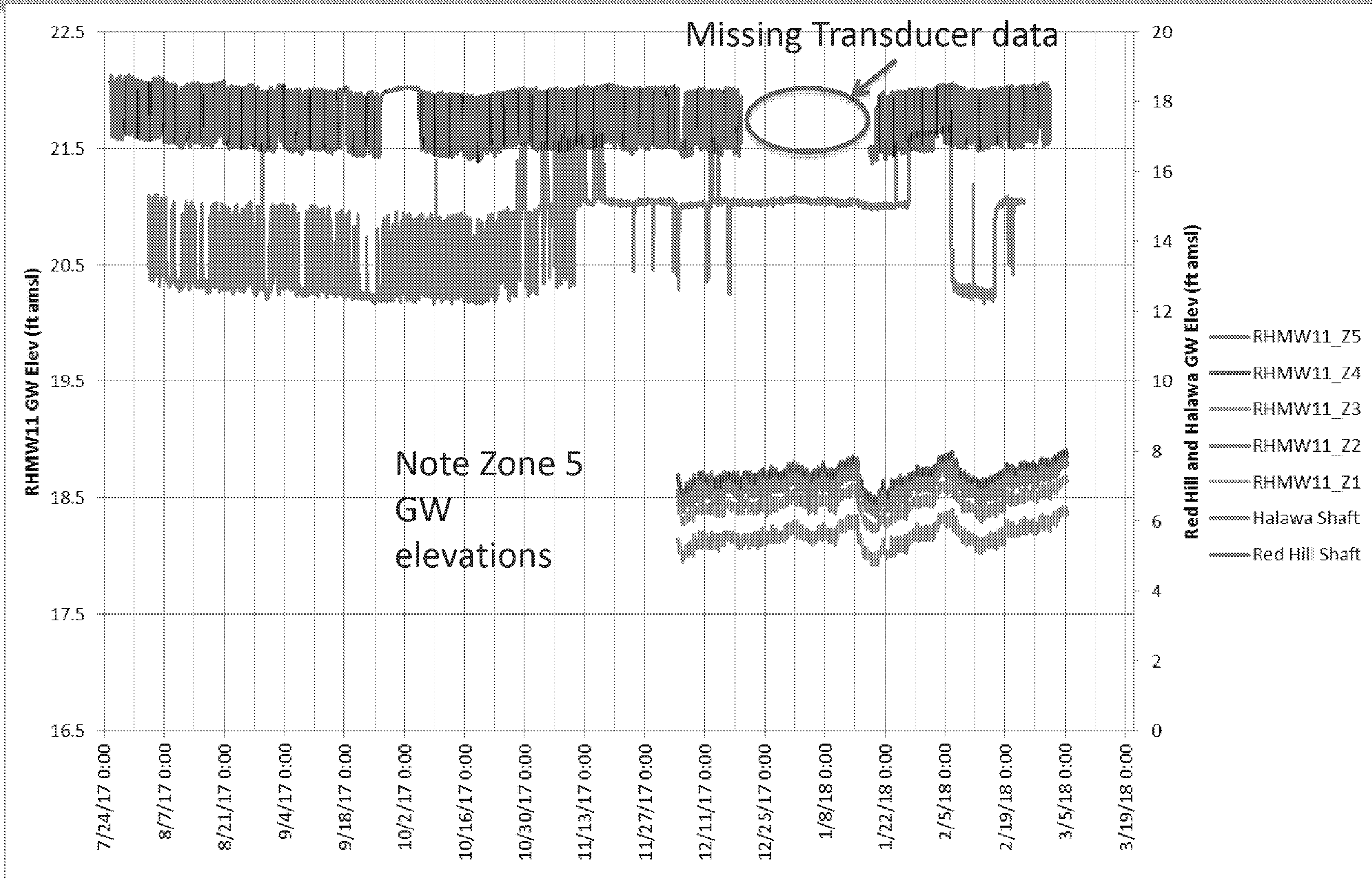
# RHMW11 ZONES 1 THROUGH 8



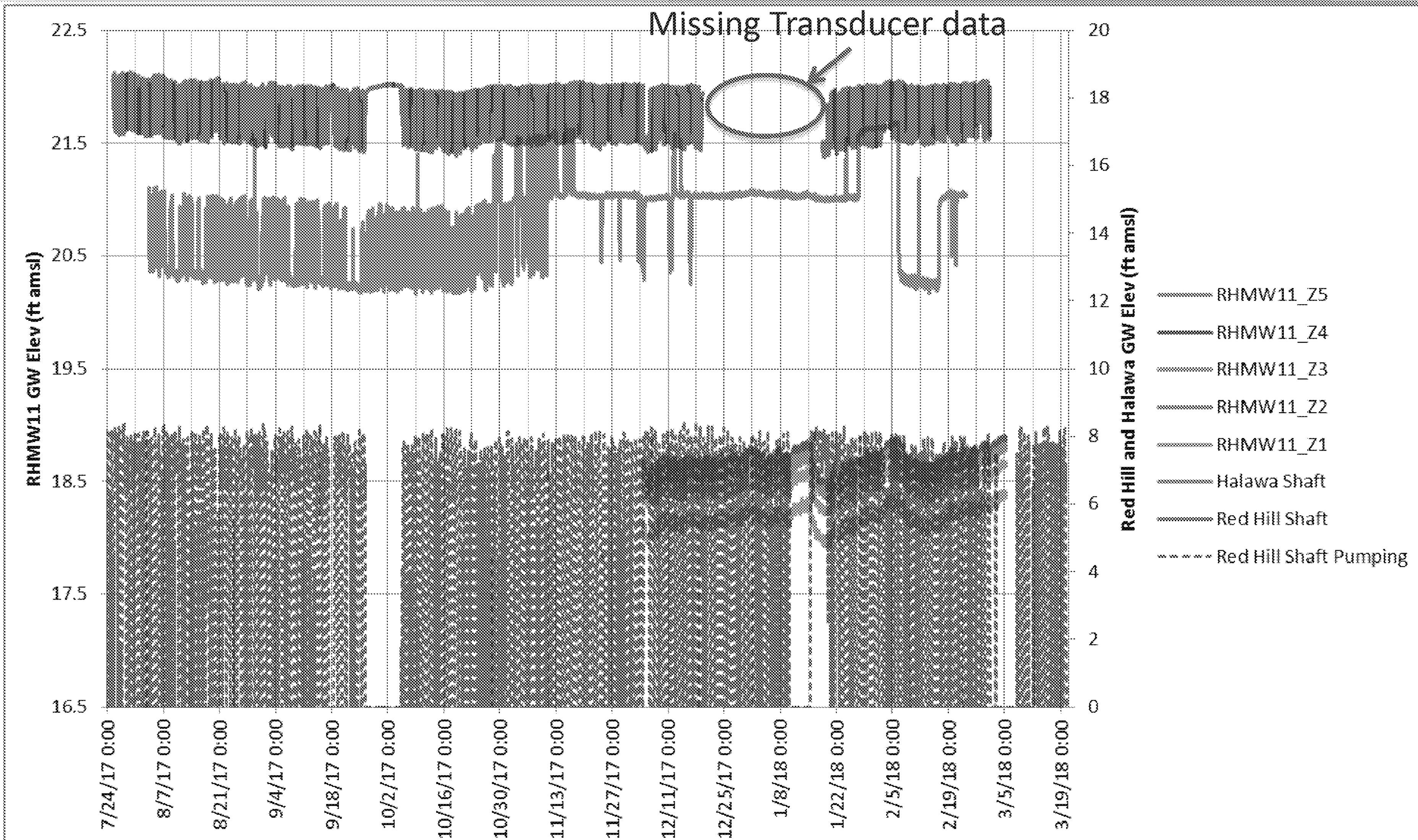



ED_006532_00002564-00018

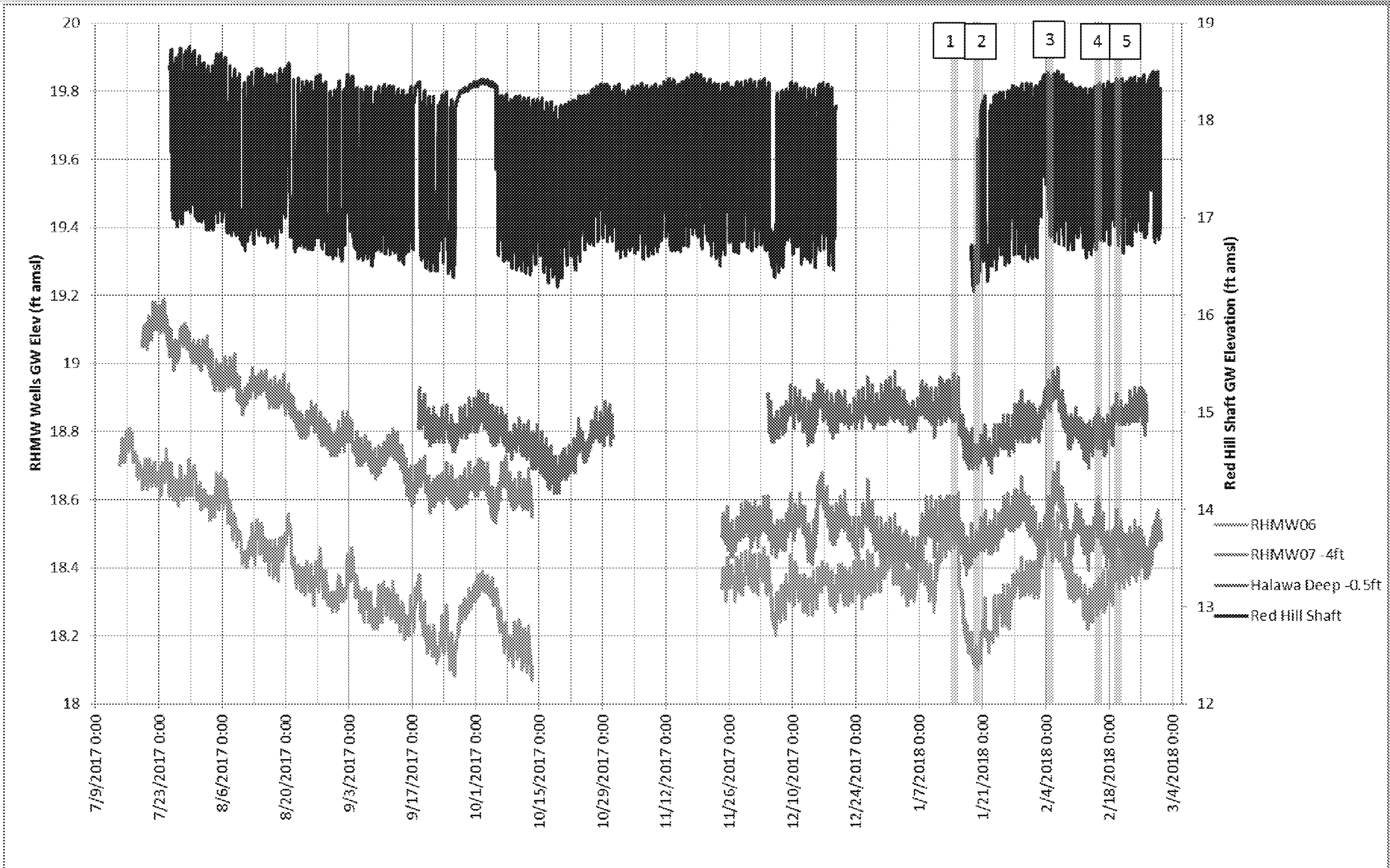
# RHMW11 ZONES 1 THROUGH 5



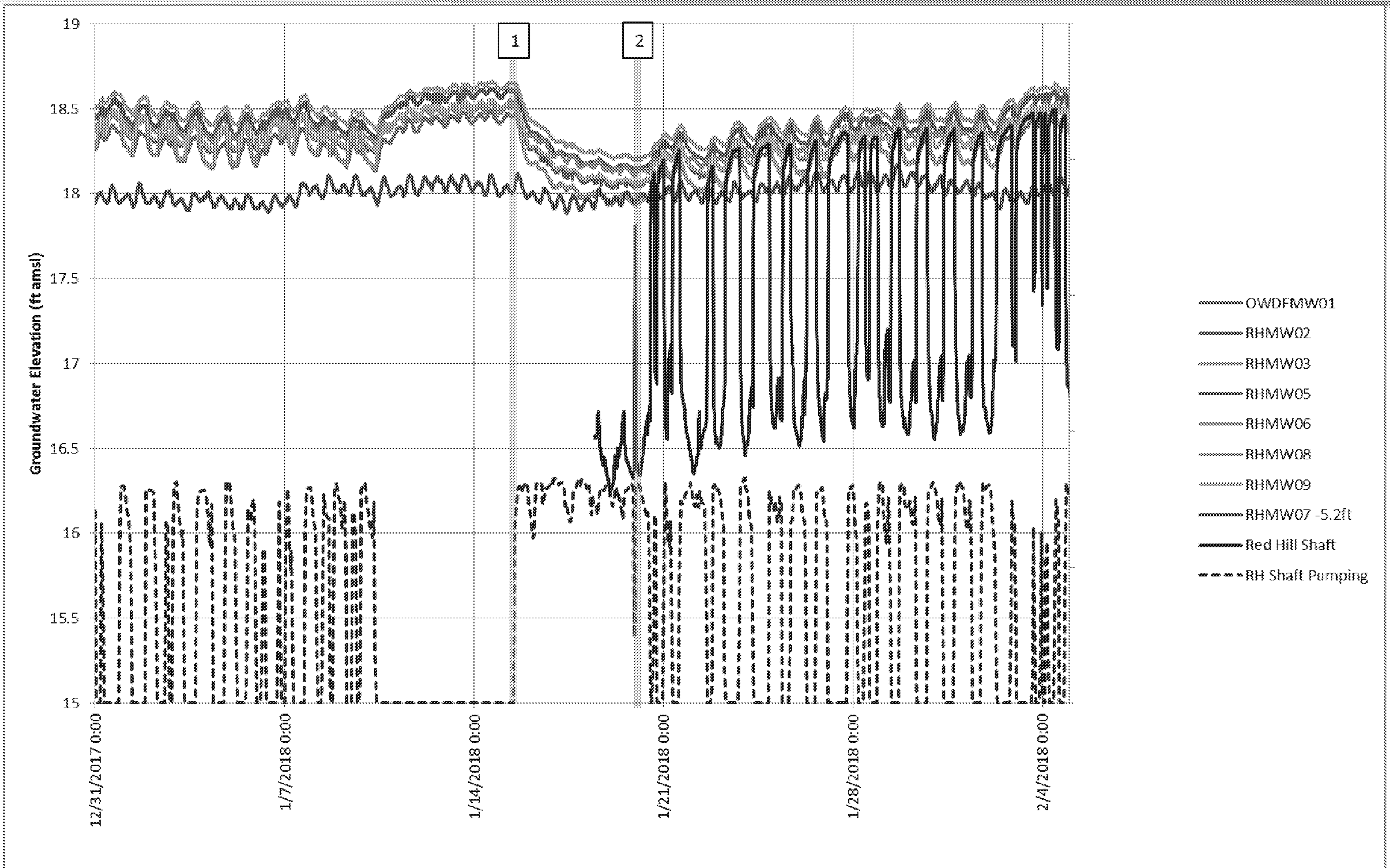
# RHMW11 ZONES 1 THROUGH 5 WITH RED HILL PUMPING



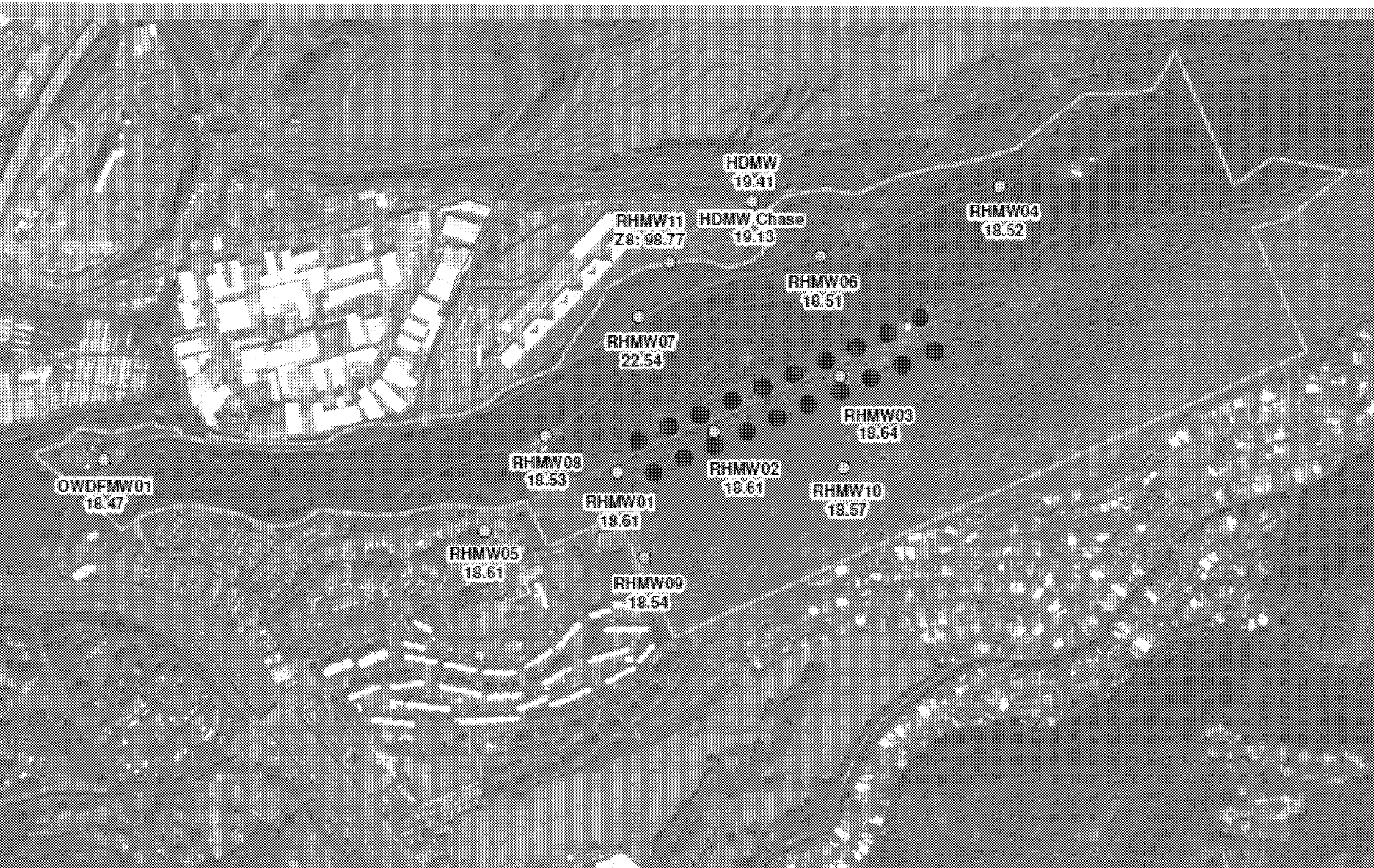
# RHMW06, RHMW07, HALAWA DEEP, RED HILL SHAFT



# EFFECT OF RHS PUMPING

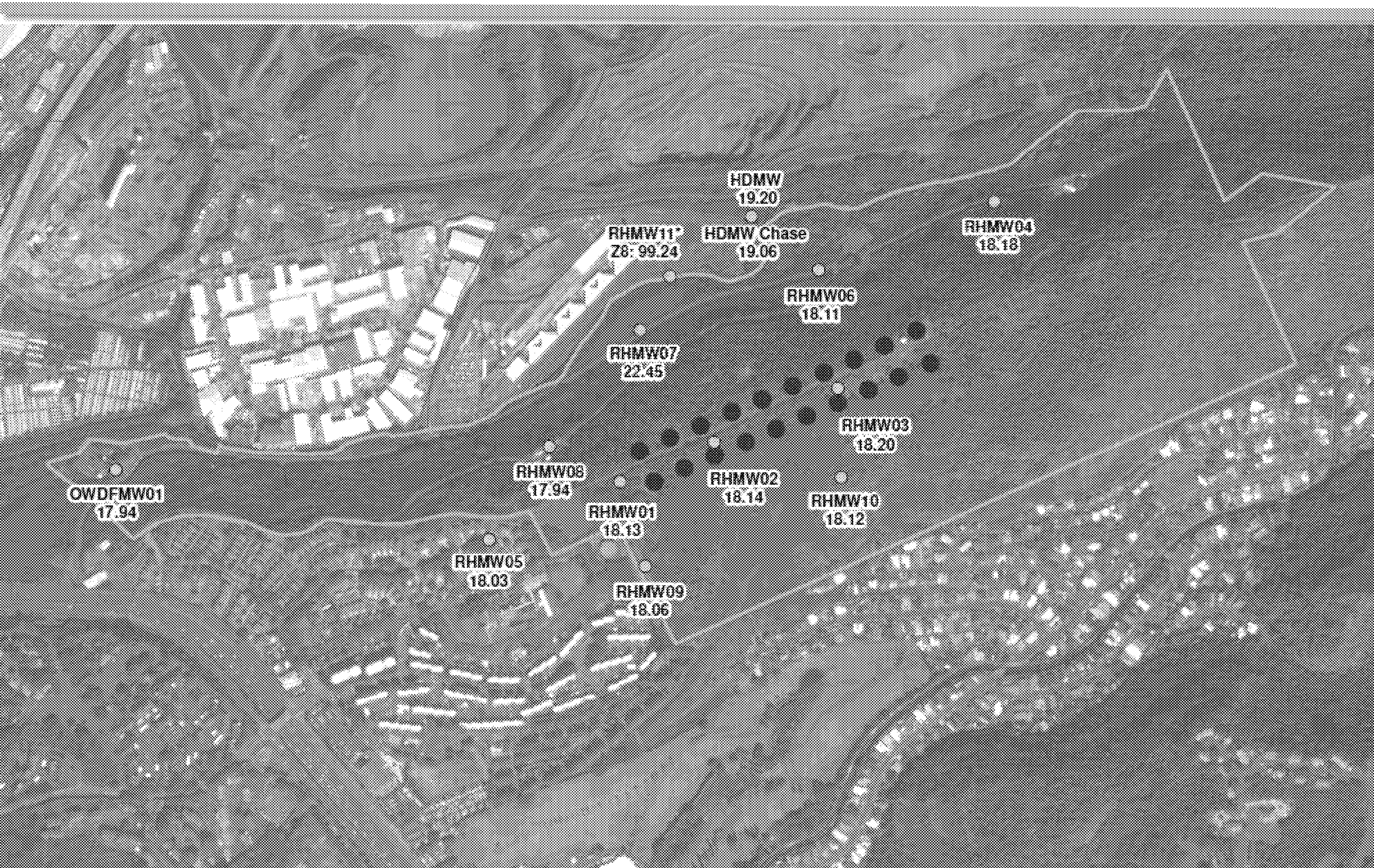


# TIME 1 - RED HILL SHAFT OFF (AT MAX RECOVERY) HALAWA SHAFT AVERAGE PUMPING

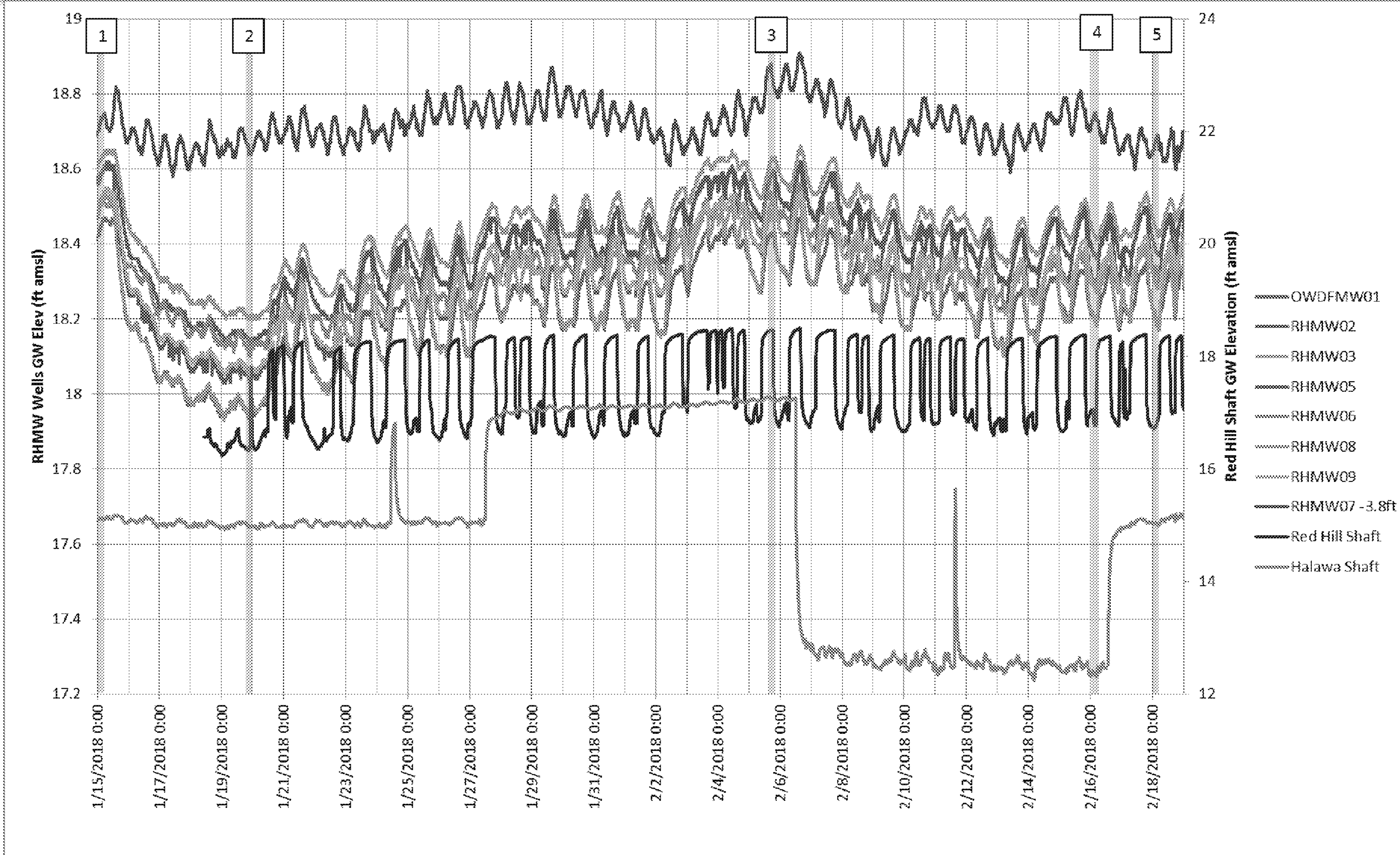



ED_006532_00002564-00023

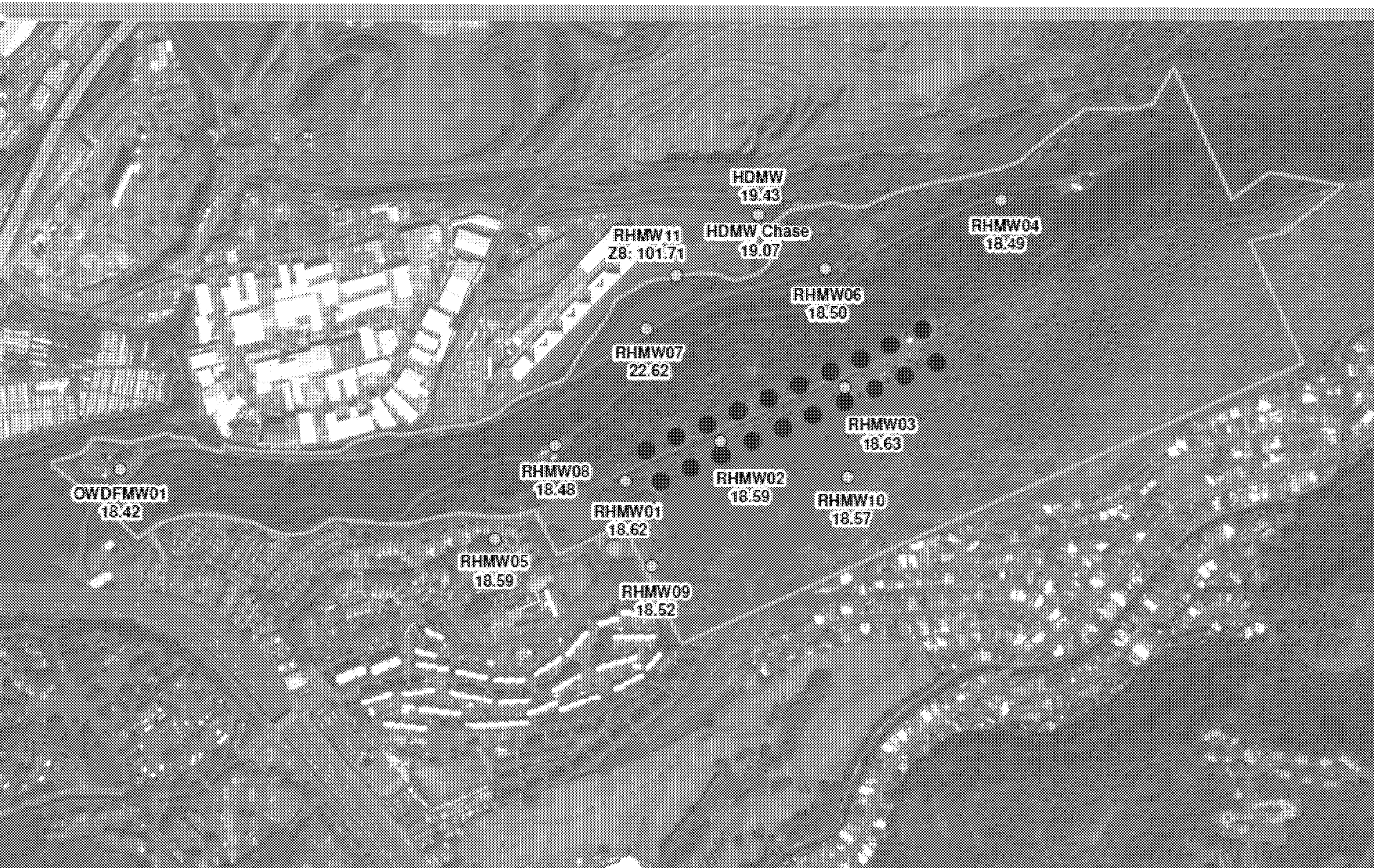
# TIME 2 - RED HILL SHAFT AT CONTINUOUS PUMPING
# HALAWA SHAFT AVERAGE PUMPING



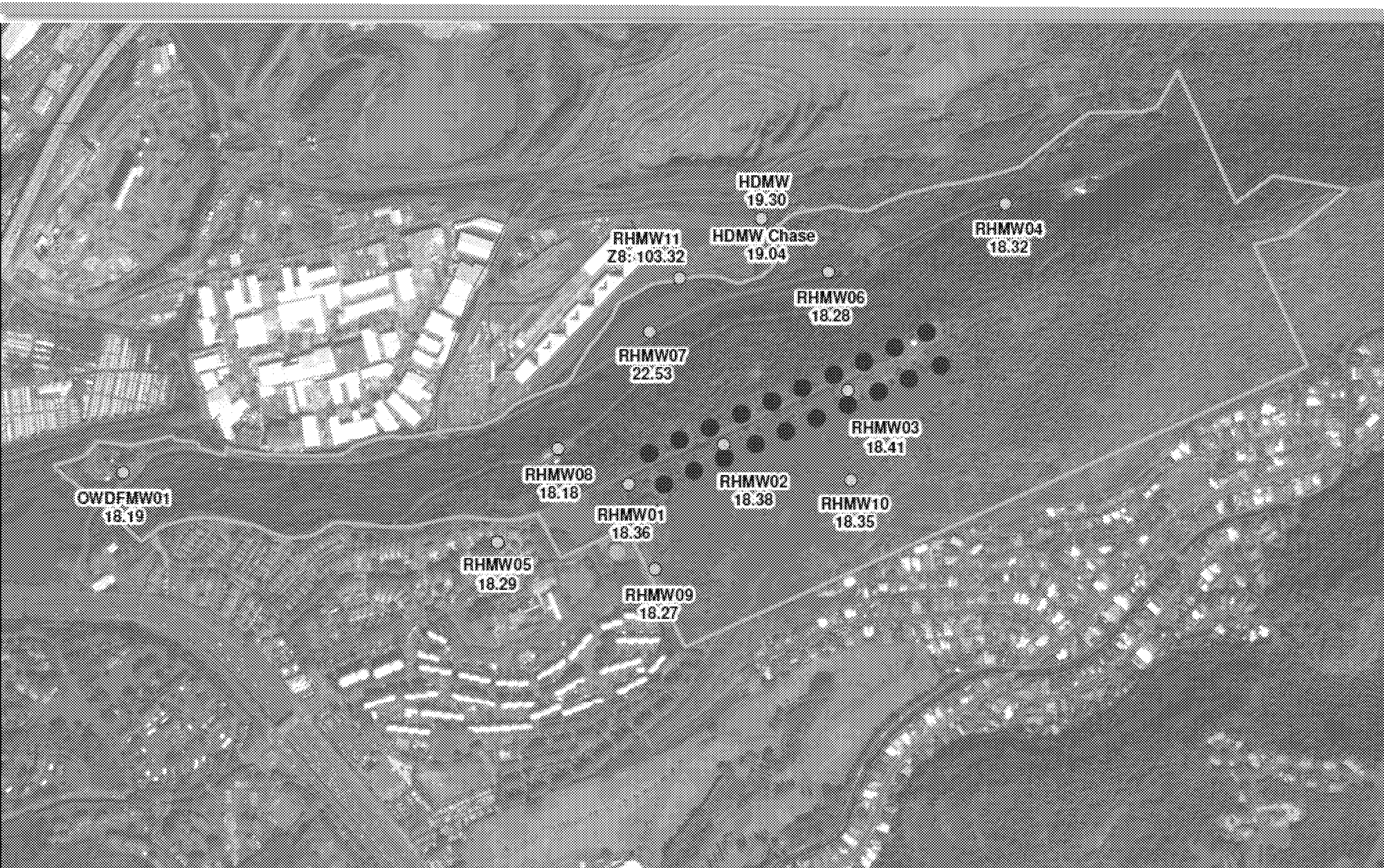
# EFFECT OF HALAWA SHAFT PUMPING



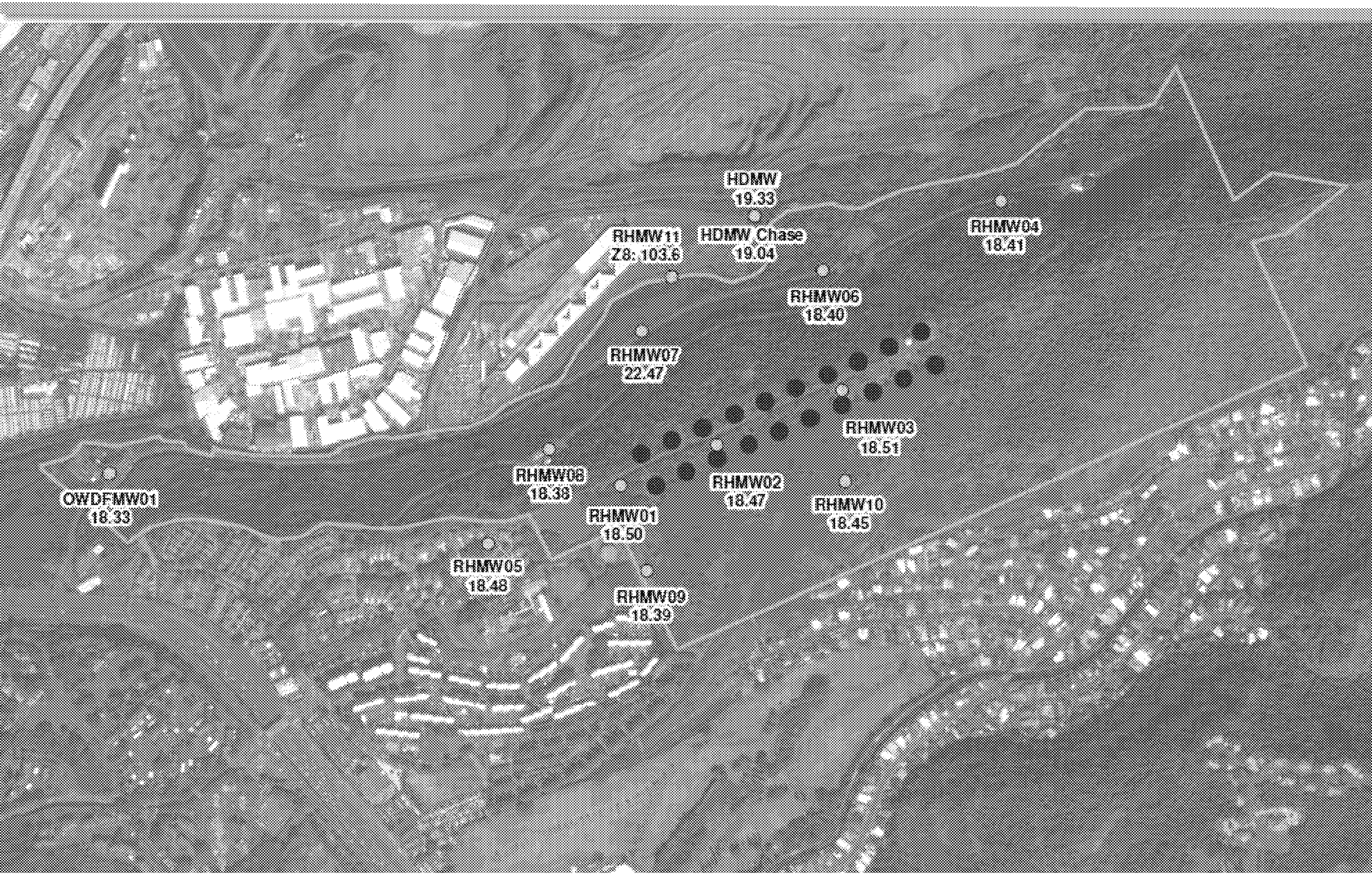
# TIME 3 - RED HILL SHAFT BUSINESS AS USUAL (BAU) PUMPING, HALAWA SHAFT OFF



# TIME 4 - RED HILL SHAFT BAU
# HALAWA SHAFT AT MAX PUMPING



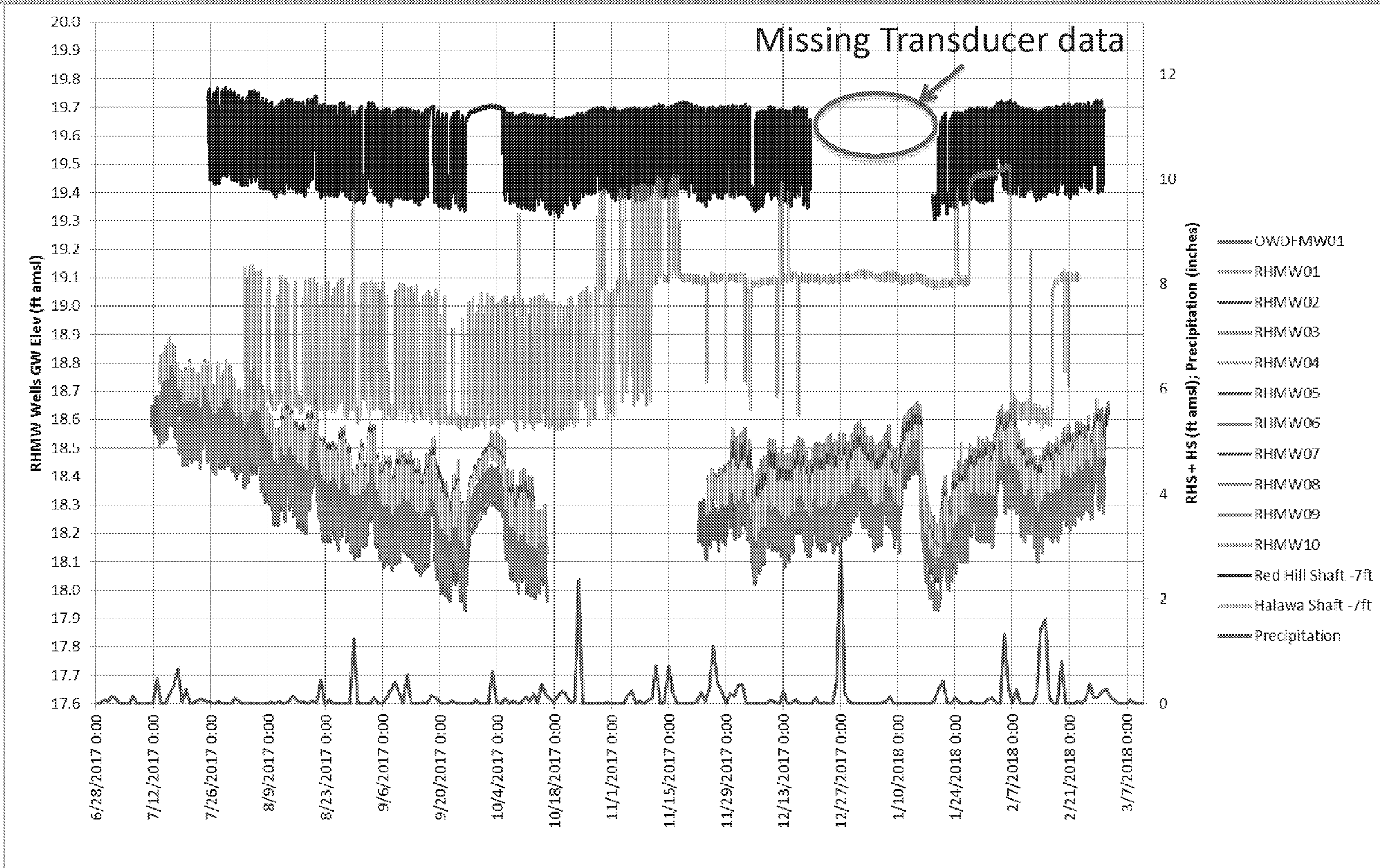
# TIME 5 - RED HILL SHAFT BAU
# HALAWA SHAFT AVERAGE PUMPING



# FROM DOH PROVIDED AT APRIL 2018 GWFMWG MEETING

- There must be a groundwater gradient in the hypothesized direction of groundwater flow.
- In Hawaii the rule of thumb is that the gradient toward a pumping center should be about a foot.

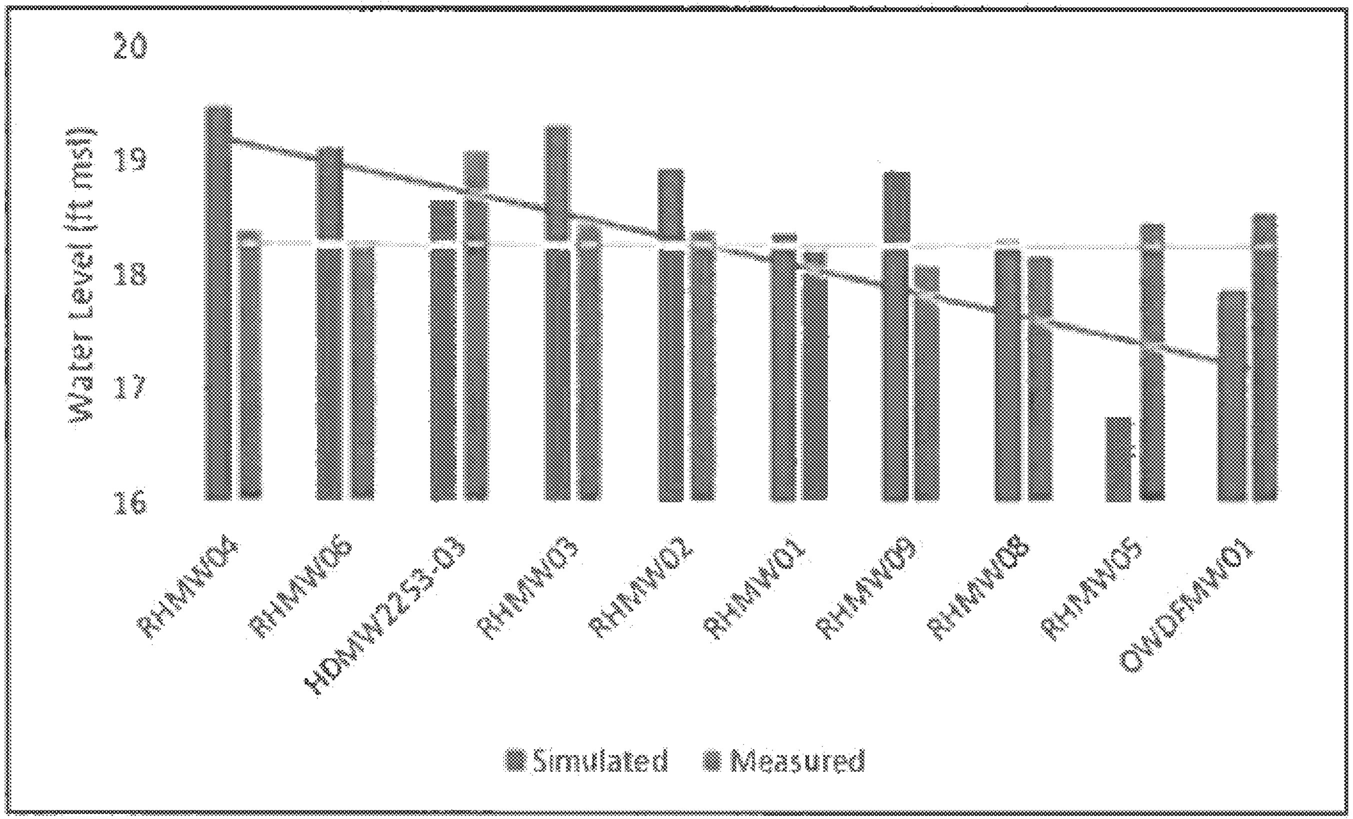
# INFLUENCE OF PRECIPITATION?





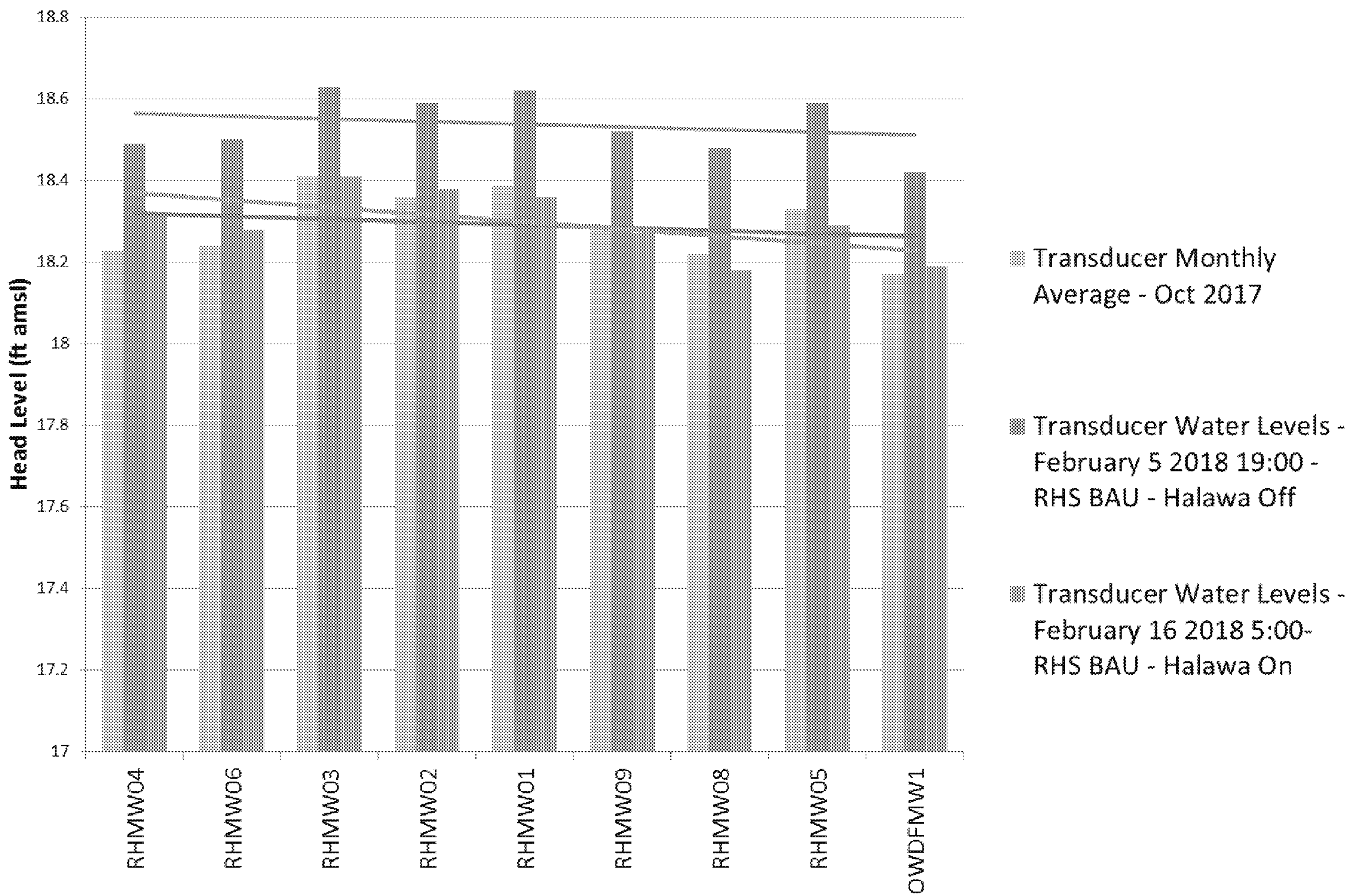

ED_006532_00002564-00030

# 2/20/18 DOH LETTER REGARDING GROUNDWATER LEVELS



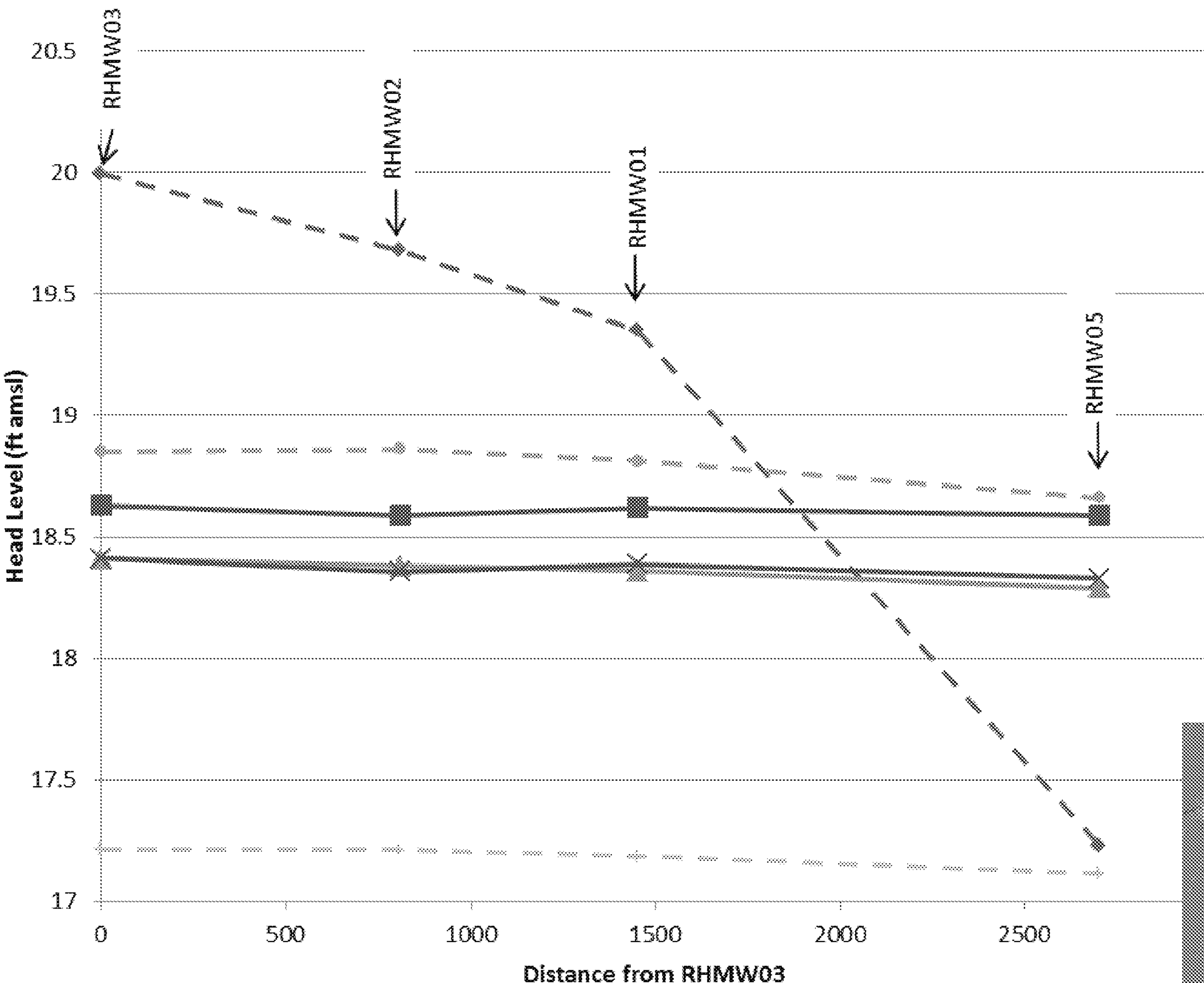

The bar graph below compares the modeled groundwater elevations (blue bars) to those measured in 2017 (orange bars). The data are arranged going from RHMW04, the most upslope well, to OWDFMW01, the most down slope well. A visually estimated trend line is drawn for each data set. The values for the modeled groundwater elevations were derived by applying the modeled residuals in Slide 30 to the average of water level measurements during the July and November rounds of groundwater sampling. For the modeled capture zone shown on Slide 57 to be valid there should reasonable agreement between the trend in the modeled and measured groundwater elevations. Clearly this is not the case...

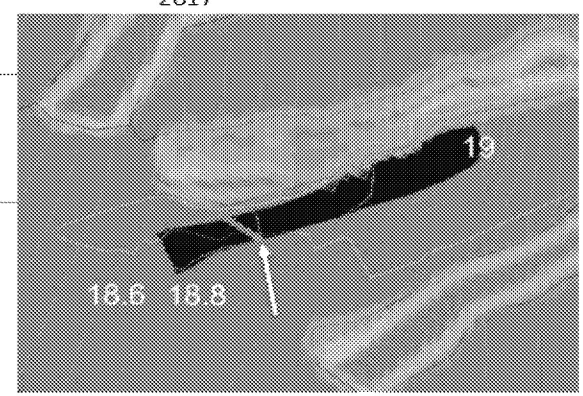
# PARTIAL 2017/2018 SYNOPTIC DATA



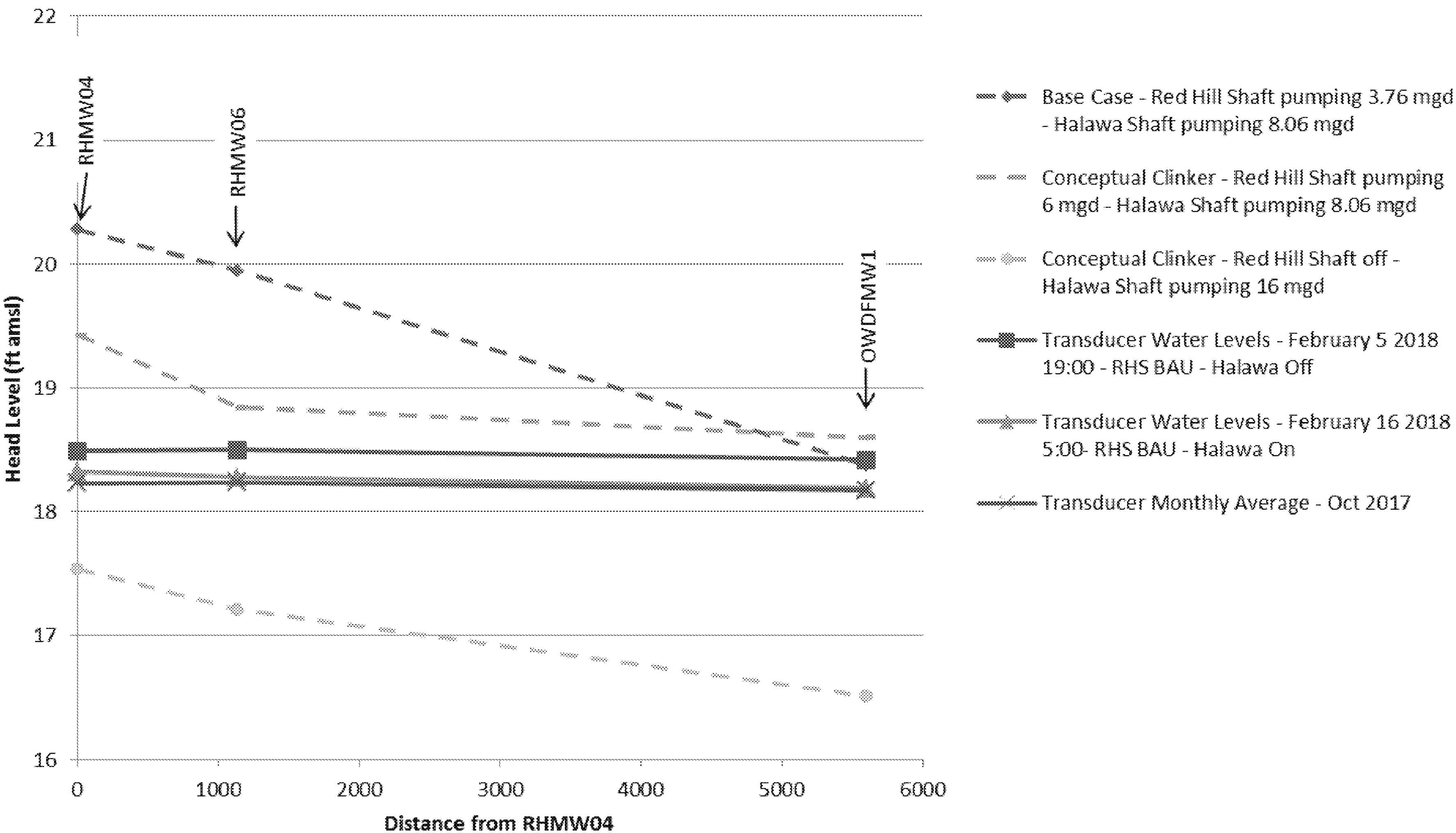
# ADDITIONAL TRANSECTS

# WATER LEVELS FROM RHMW03 TO RHMW05



# WATER LEVELS FROM RHMW04 TO OWDFMW1



# ISSUES AND ACTION ITEMS FROM LAST MEETING AND DOH/BWS COMMENTS

# APPROACH TO MODELING BASALT

- The Navy has reviewed:
  - Hunt Jr., C. D. 1996. Geohydrology of the Island of Oahu, Hawaii. Professional Paper 1412B. U.S. Geological Survey.
  - Izuka, S. K., J. A. Engott, M. Bassiouni, A. G. Johnson, L. D. Miller, K. Rotzoll, and A. Mair. 2016. *Volcanic Aquifers of Hawai'i—Hydrogeology, Water Budgets, and Conceptual Models*. Scientific Investigations Report 2015–5164. Water Availability and Use Science Program. U.S. Geological Survey.
  - Oki, D. S., W. R. Souza, E. I. Bolke, and G. R. Bauer. 1996. *Numerical Analysis of Ground-Water Flow and Salinity in the Ewa Area, Oahu, Hawaii*. Open-File Report 96-442. U.S. Geological Survey.
  - Oki, D.S., W. R. Souza, E. I. Bolke, and G. R. Bauer. 2005. *Numerical Simulation of the Effects of Low-Permeability Valley-Fill Barriers and the Redistribution of Ground-Water Withdrawals in the Pearl Harbor Area, Oahu, Hawaii*. Scientific Investigations Report 2005-5253. U.S. Geological Survey.
  - Rotzoll, K., and A. I. El-Kadi. 2007. *Numerical Ground-Water Flow Simulation for Red Hill Fuel Storage Facilities, NAVFAC Pacific, Oahu, Hawaii*. Prepared for The Environmental Company (TEC). Honolulu, HI: University of Hawaii, Water Resources Research Center. August.
  - Wentworth, C. K. 1938. *Geology and Ground Water Resources of the Palolo-Waialae District*. Honolulu, HI: Board of Water Supply.
  - Whittier, R. B., K. Rotzoll, S. Dhal, A. I. El-Kadi, C. Ray, and D. Chang. 2010. *Groundwater Source Assessment Program for the State of Hawaii, USA: Methodology and Example Application*. *Hydrogeology Journal* 18 (3): 711–723.

# APPROACH TO MODELING BASALT

- References continued:


  - Soroos, R. L. 1973. *Determination of Hydraulic Conductivity of Some Oahu Aquifers with Step-Drawdown Test Data*. M.S. Thesis, University of Hawaii, Honolulu, Hawaii.,
  - Dale, R. H. 1974. *Relationship of Ground-Water Tides to Ocean Tides: A Digital Simulation Model*. Ph.D. dissertation, Geology and Geophysics, Honolulu, HI: University of Hawaii at Manoa.
  - Mink, John F., and L. Stephen Lau. 1980. *Hawaiian Groundwater Geology and Hydrology, and Early Mathematical Models*. Project Completion Report for: Transfer of Hawaii Water Research Results by User-Oriented Publications, Phase II, OWRT Project No.: A-077-HI. Technical Memorandum Report No. 62.
  - Nichols, W.D., P. J. Shade, and C.D. Hunt, Jr., 1996. *Summary of the Oahu, Hawaii, Regional Aquifer-System Analysis*, U.S. Geological Survey Professional Paper 1412-A.
  - Podgorney, R.K., T.R. Wood, B. Faybishenko, and T.M. Stoops. 2000. *Spatial and Temporal Instabilities in Water Flow through Variably Saturated Fractured Basalt on a One-Meter Field Scale*, in Dynamics of Fluids in Fractured Rock, American Geophysical Union. B. Faybishenko, P.A. Witherspoon, and S.M. Benson, Editors. Pp. 129-146.
  - Souza, W.R., and Voss, C.I., 1987, *Analysis of an anisotropic coastal aquifer system using variable-density flow and solute transport simulation*: Journal of Hydrology, v. 92, p. 17-41.


**Are we missing anything significant?**

# APPROACH TO MODELING BASALT

- There is a range of effective material properties that are plausible and have been used in modeling efforts. The current models encompass that range of properties thus establishing a range of conditions when applied towards evaluating migration rates and directions
- Discuss Geologic Framework and CSM
- Use of average conditions is protective of Halawa Shaft
- One model includes local heterogeneity consistent with a conceptual high-K clinker zone along Red Hill ridge
- Use homogenous anisotropic equivalent porous medium
- Additional discussion on heterogeneity follows

# SAPROLITE EXTENT AND HYDRAULIC PROPERTIES

- Saprolite depth and hydraulic properties are conservatively considered in the interim modeling effort
- While the base-case interim model shows that saprolite extends 60 feet below the water table, the December 2018 model will reflect our CSM which will be based on all available data;
  - Literature
  - Existing well logs
  - Seismic survey
  - Permeability testing
  - New monitoring wells (e.g., RHMW11 and other new wells to come)
  - Water level data from synoptic and other sources
  - HART borings
  - Geologic mapping
- Saprolite hydraulic properties are on the high side of measurements in the base case model
- Sensitivity models for saprolite hydraulic properties include lower and higher hydraulic conductivity values
- A sensitivity model also evaluates impact of no saprolite underneath the valleys
- CSMs from various models;
  - Oki et al. 2005
  - DON 2007 (Rotzoll, K., and A. I. El-Kadi. 2007)
  - Whittier et al. 2010 (SWAP Model)
    - Similar objectives to current modeling effort

# BWS COMMENT ON MODEL LAYERING

- Among the figures that the Navy should present to demonstrate their claim that the top model layer is based on the location of the water table are maps that show the difference between the simulated steady-state water table and the top of the model.
  - The Navy does not make this claim
  - The following slides discuss the model layering concepts

# BWS COMMENTS CONTINUED

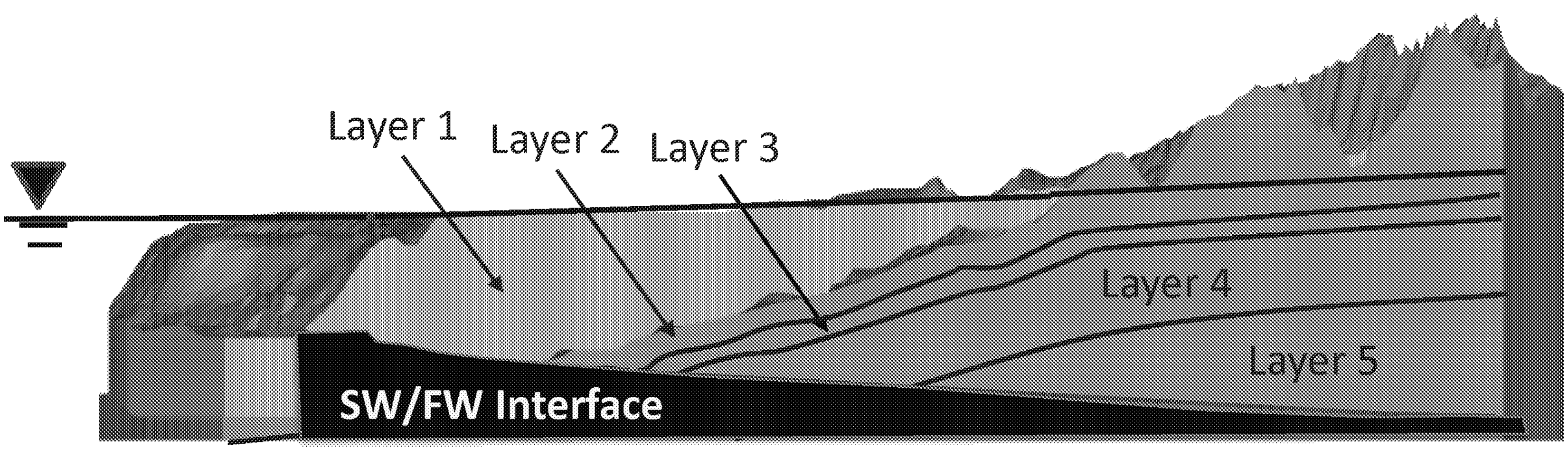
- … discuss how the Navy will compare simulated and observed water levels, pumping rates and chemical concentrations
  - Flow model calibration metrics were provided in previous presentations and will be provided in the interim modeling report
  - Details of how the flow model calibrations performed were also provided in previous presentations and will be provided in the interim modeling report
  - December 2018 flow model calibration will be detailed in upcoming meetings and the flow model report
  - Transport model calibration to COPCs will be evaluated at the final model stage

# BWS COMMENTS CONTINUED

- ...explain why the current model layering is adequate and requires no further adjustments.
  - The following slides discuss the layering of the interim model as previously discussed in multiple meetings and why it is adequate
  - The December 2018 model numerical layering will be adjusted to accommodate solute transport

# MODEL LAYERING

- Layer 1: Valley fill in the valleys and caprock in southwest
- Layers 2 and 3: Saprolite under the valleys and basalt elsewhere
  - Saturated thickness:
    - Layer 2: 20 feet
    - Layer 3: 40 feet
- Layers 4 and 5: Basalt
  - Saturated thickness:
    - Layer 4: 80 feet
    - Layer 5: Variable



# MODEL LAYERING

- Basalt and saprolite are discretized using multiple model layers to provide finer vertical resolution for transport and to capture vertical gradients
- Bottom of layers 2, 3, 4 and 5 approximately follow the conceptual water table surface where caprock is absent
  - Provides fine resolution at and below water table
  - Avoids dry cells of large thickness above water table
  - Low vertical hydraulic conductivity of basalt represents vertical structure of basalt
  - MODFLOW equations strictly represent horizontal and vertical directions
  - Vertical freshwater level gradients are relatively small except within saprolite or at pumping locations – this was also noted in the USGS (Oki et al. 2005) model

# BWS COMMENT ON MODEL LAYERING

- The thickness and dip angle of the model layer influences simulated flow and transport. Our concern with the model layer thickness and dip angle is whether they are generally aligned with the properties and features of the basalt that influence actual groundwater flow. To investigate this concern model layers should be evaluated in the light of the single geological conceptual model, geologic profiles of different lava flows in logs or boreholes, mapped dip angles, observed faults and full patterns.
  - The premise here is incorrect. The dip angle of the model layer is not representative of the dip angle of the geological layer in MODFLOW.
  - Other numerical modeling efforts have the same conceptualization for basalt

# RED HILL AREA BASALT GEOMETRY/GEOLOGY

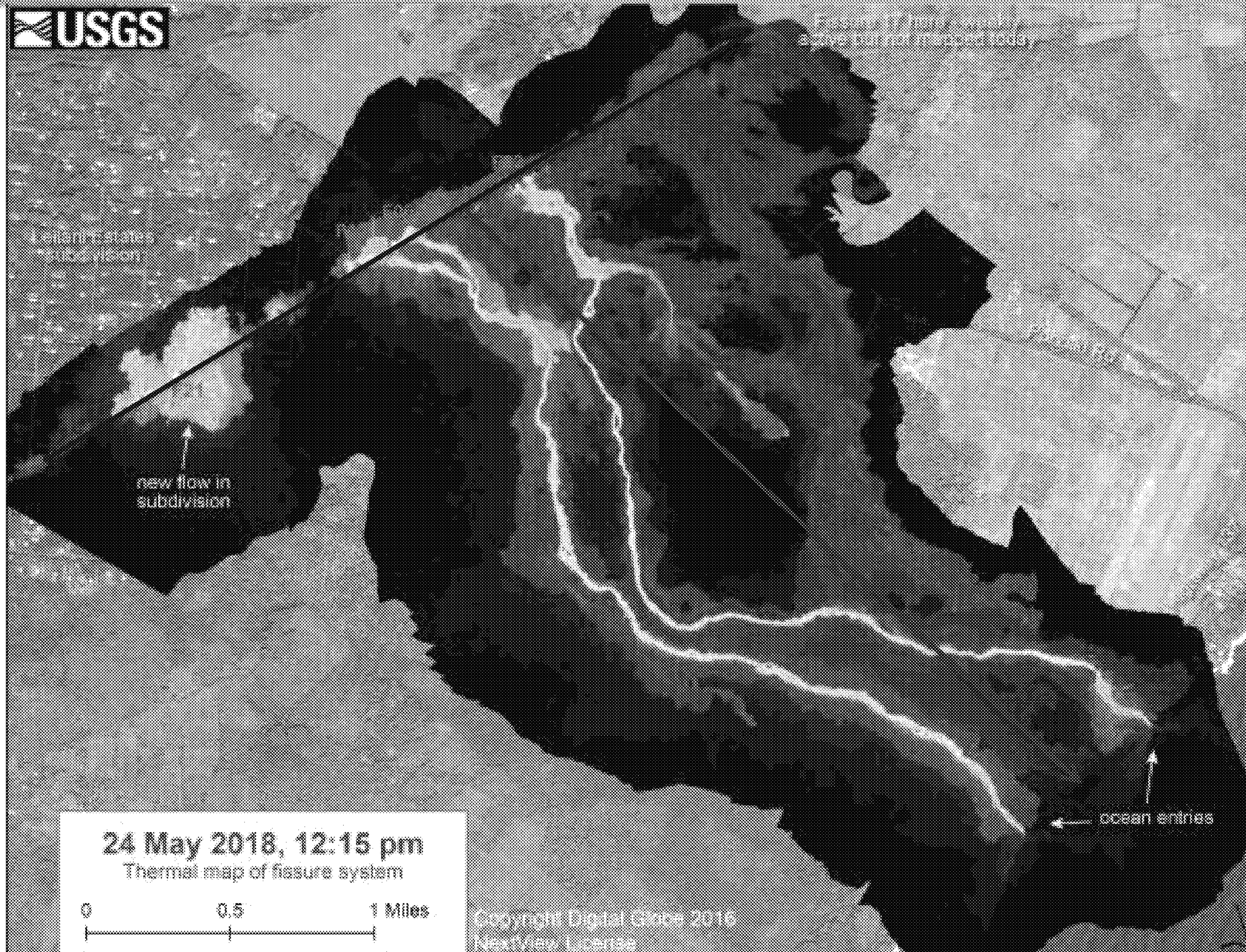
- Macdonald 1941 - Geology of the Red Hill and Waimalu Areas, Oahu: "The lava flows form sheets 3 to 50 feet thick, with very irregular tops and bottoms, sloping gently southwestward. Many of them thin toward the southwest."
- "The lavas moved down the slope toward the southwest (~225°) as relatively narrow streams. Their continuity along the ridge at Red Hill is therefore greater than across the ridge." Recent mapping indicates the dip direction averages to the SSW in the Red Hill Area (~195° to 205°).
- Hunt Jr. (1996) states that "Wentworth and Macdonald (1953, p. 31) listed measurements for 22 historical flows on Mauna Loa and Kilauea on the island of Hawaii, which presumably are typical of flows on Oahu as well. The flows on Hawaii average about 15 mi in length and about one-half mile in width." The distance from the NW Rift zone of Ko'olau volcano to Red Hill is approximately 8 miles. Flow core widths could be significantly less than one-half mile; potentially hundreds of feet wide.
- According to Macdonald 1941, many flows thicken or thin rapidly across the ridge, and some pinch out altogether at Red Hill. This implies the existence relatively narrow flows. If clinker bridges are present, they would be pathways for lateral and vertical flow at the edges of a lava flow, but limited in areal extent perpendicular to lava flow direction.

# RED HILL AREA BASALT GEOMETRY/GEOLOGY

- Lava flows are controlled by topography and follow the natural drainage pattern. Recent thermal imagery of the flows in the Pahoa area of the big Island shows that flows do meander typically at 45° relative to the baseline flow direction (fall line). At Red Hill, a meander in a lava flow would need to exceed one mile transverse to the axis of the flow to intercept Halawa Shaft.
- Macdonald 1941: "The pahoehoe flows are fed by lava moving through tubes in the interior of the flow, most of them only a foot or two across but a few reaching diameters of tens of feet. Sometimes the liquid lava drains away from these tubes leaving them partly or entirely empty."
- Lava tubes are constrained by the width of a lava flow they are part of. With that, it is highly unlikely that there may be lava tubes from Red Hill area that would provide a conduit or pathway toward Halawa Shaft, (i.e., the unlikely geometry that would allow a lava tube somewhere near the water table under the Red Hill facility to be oriented all the way across (under or around) the saprolite in modern day North and South Halawa Valleys, and then extend all the way to the Halawa shaft.)

# A MODERN DAY EXAMPLE

# A MODERN DAY EXAMPLE



# PUBLICATIONS

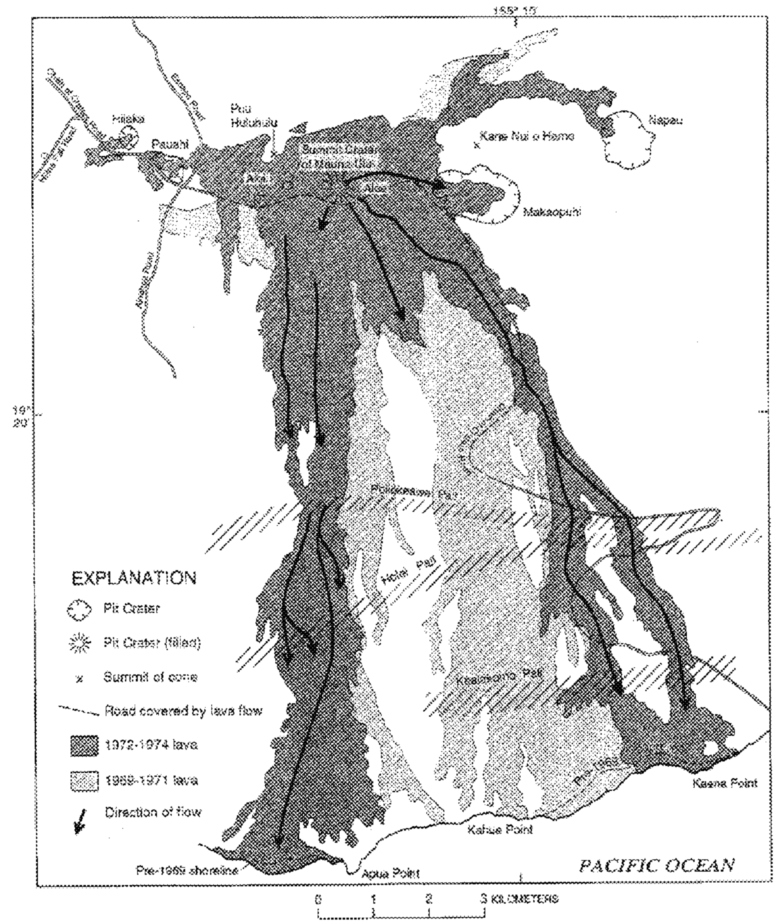
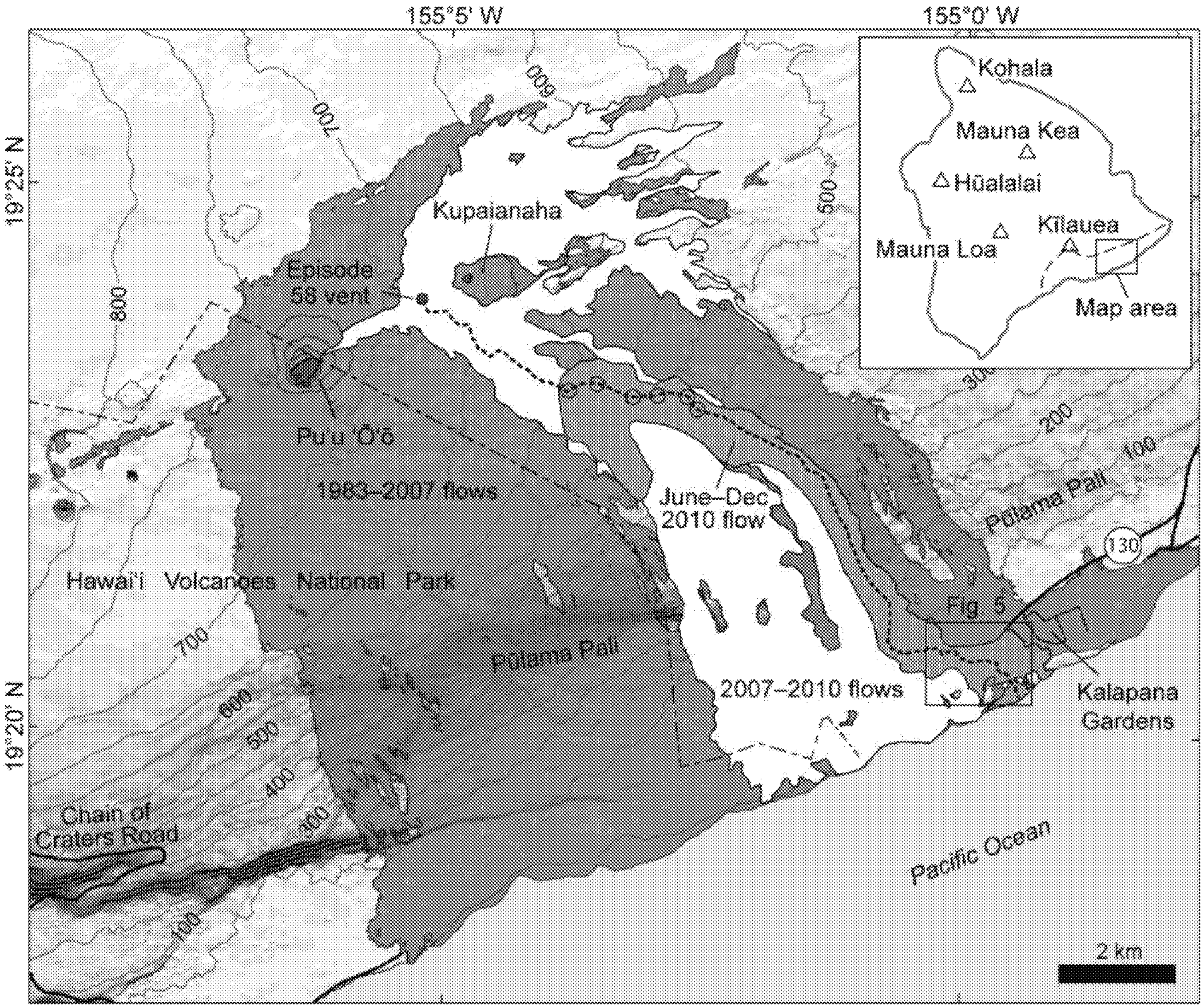



**Fig. 1** Map showing lava fields from 1969–1971 (*light shading*) and 1972–1974 (*dark shading*) activity at Mauna Ulu (adapted from Tilling et al. 1987, Fig. 16.2). Large areas of 1969–1971 lava were buried by the younger lava. Map shows generalized routes of major lava tubes (after Holcomb 1976). Road shown on map is route prior to Mauna Ulu eruption; this highway has subsequently been partly rerouted

Mattox et al. 1993

Peterson et al. 1994

# PUBLICATIONS

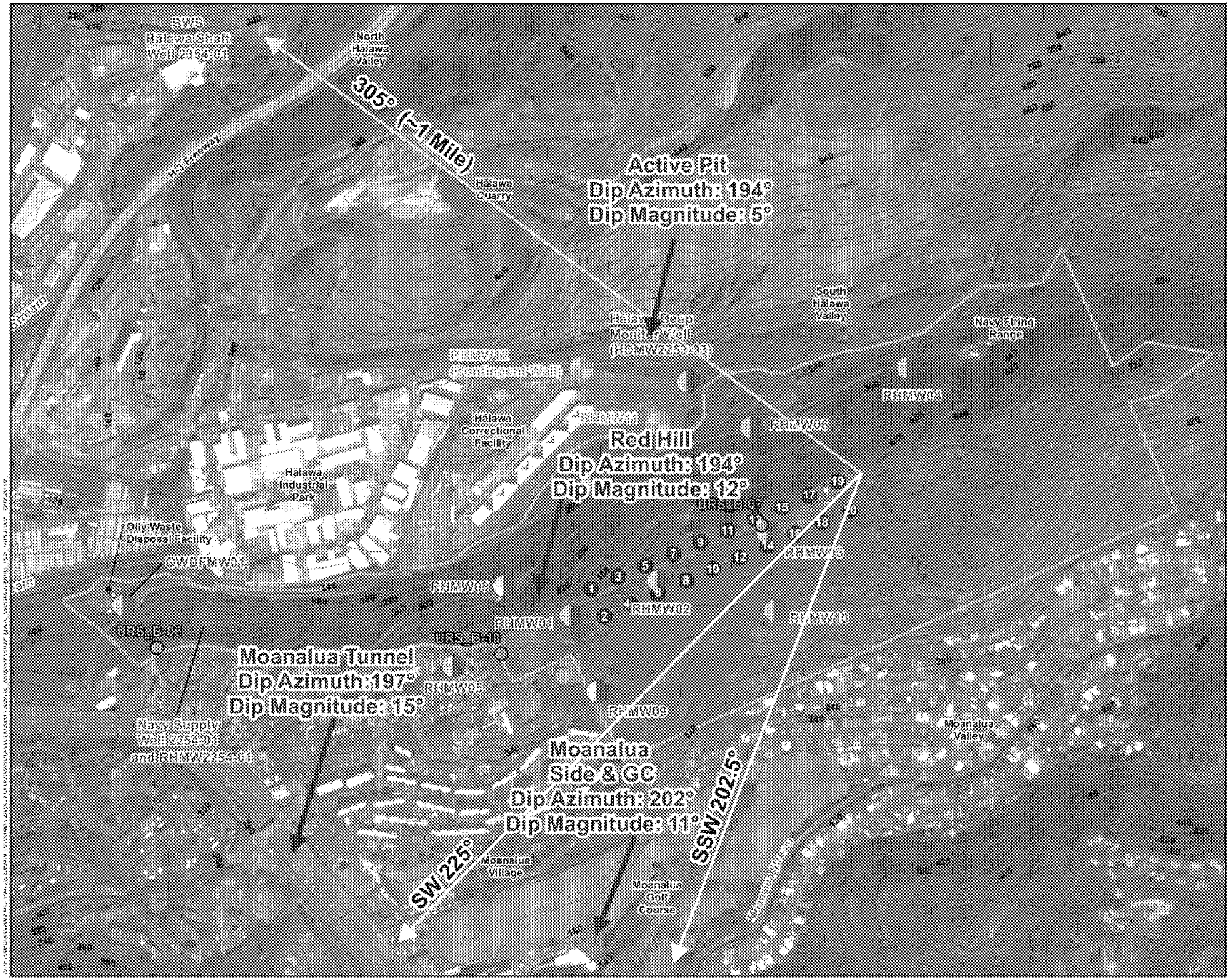



Orr et al. 2015

# GEOLOGICAL MAPPING UPDATE

- South Halawa Valley (north) side of Red Hill – May/June 2017
- Moanalua Golf Course and Moanalua Valley (south) side of Red Hill – May 16, 2018
- Active pit at Halawa Quarry – May 18, 2018
- Moanalua Water Tunnel – May 21 & 22, 2018

# RED HILL AREA BASALT GEOMETRY/GEOLOGY

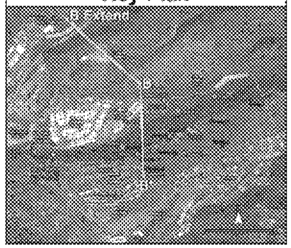





ED_006532_00002564-00054

# RED HILL AREA BASALT GEOMETRY/GEOLOGY

**Key Plan**

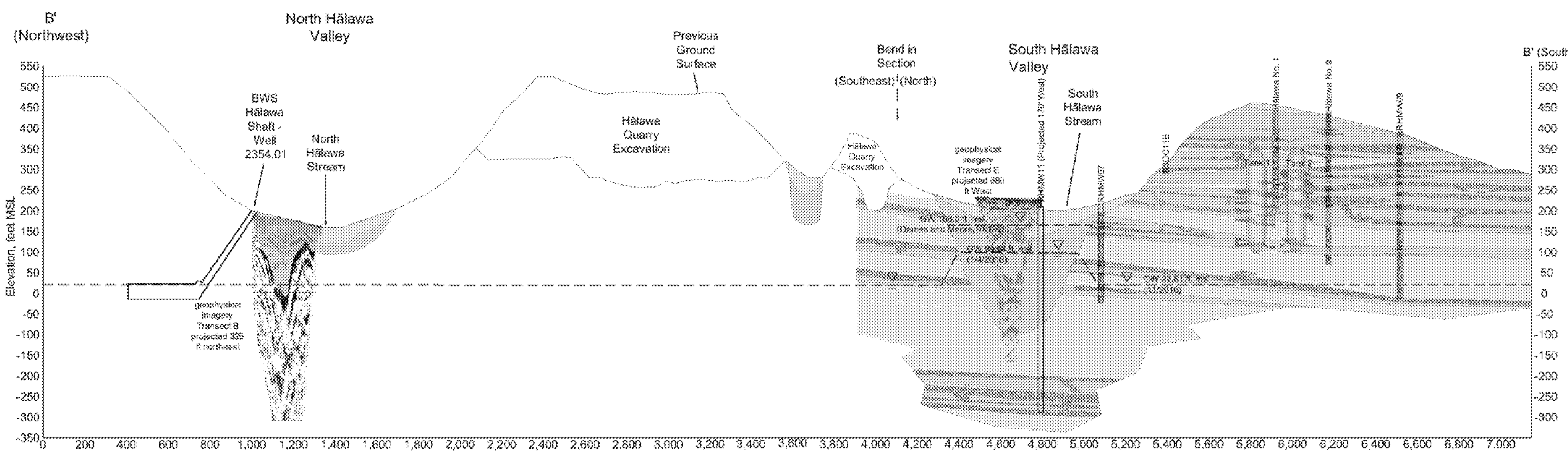



**Legend**

- Valley Fill
- Saprolite
- Basalt - A'ā Clinker
- Basalt - Massive A'ā
- Basalt Pāhoehoe
- Measured Groundwater (date)

**Notes**

1. RHMW07: DON 2015a
2. RHMW09: DON 2017e
3. Hālawa No. 1, 9: Macdonald 1941
4. Outcrop OC11B: Field Notes 2017
5. As-Built Barrel Log: DON 1943



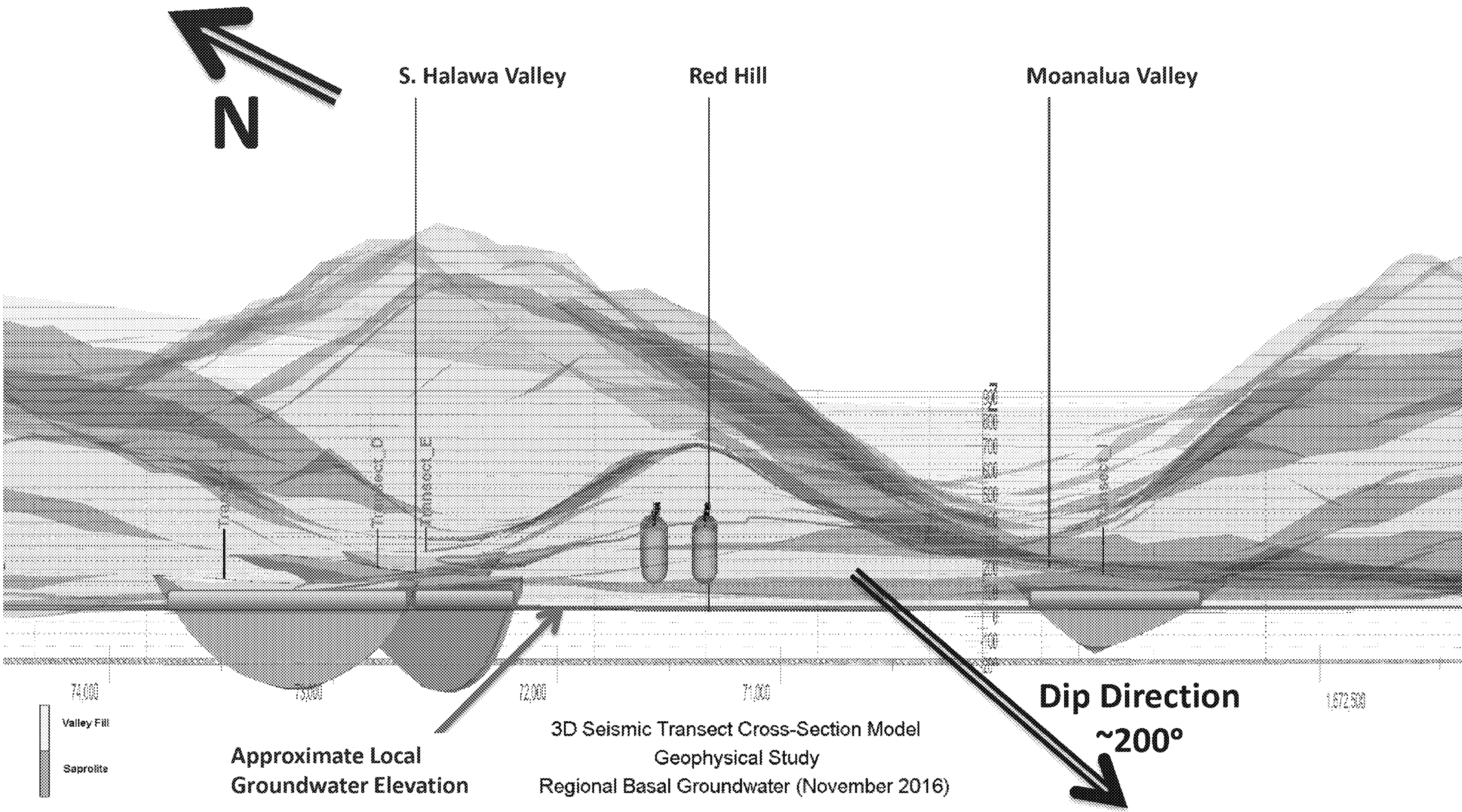

500' 0 500' 1000'

Horizontal Scale: 1" = 500', Vertical Scale: 1" = 250'

**Note: Vertical exaggeration = 1H : 2V (approximate)**

# OBLIQUE PERSPECTIVE

## View to ENE (N67°E)




3D Seismic Transect Cross-Section Model
Geophysical Study
Regional Basal Groundwater (November 2016)

# FROM BWS 4/30/18 LETTER:

During the last three groundwater meetings, BWS has expressed concerns that the Navy has ***not adequately vetted the rationale and data associated with developing steady-state models for 2006, 2015, and 2017. A concern we have expressed is whether the aquifer water levels can be properly modeled under the assumption of steady-state conditions*.**

Important requirements associated with steady-state conditions include that the input and output fluxes to the groundwater flow system are perfectly balanced such that there are no changes in water levels over time. An important property of a steady-state condition is groundwater outflows such as pumping rates equal groundwater inflows such as recharge, so that water levels do not change over time.

Among our concerns for using the assumption of steady-state conditions at the RHBFSF is that the Red Hill Shaft typically pumps a few hours every day and the rate is several million gallons a day. The ***pulsing of the water levels associated with the cyclic pumping may not allow the water levels to reach equilibrium with an average pumping rate*.**

Another concern is that the water levels and pumping ***rates that were used by the Navy to model steady-state conditions were selected because they were the "best available" and not because they occurred at the best time for representing a steady-state flow*.** Based on limited information that BWS has reviewed regarding the water level and pumping data, it appears that the water level measurements that were used for the steady-state models were measured when Red Hill was not pumping. If this is the case, then the Navy interim steady-state models are not technically defensible.

# STEADY-STATE MODELING ?

- Calibration was performed as follows
  - Steady-state conditions for 2006, 2015, and 2017
  - **Transient conditions for 2006 and 2015 synoptic studies**
  - Several steady-state and transient models to evaluate impact of uncertainty
    - Results from the models bracket the observed behavior for long-term annual average conditions and synoptic study observations
- The models were applied in steady-state flow fields with extreme pumping scenarios to evaluate migration of particles – **steady-state applications are conservative**
  - Halawa Shaft cannot pump at its maximum rate of 16 MGD forever with Red Hill Shaft not pumping forever
  - Steady-state simulations impose an instantaneous effect of pumping conditions and neglect transient storage changes that dissipate impacts
  - Several models were run to evaluate impact of different recharge rates, boundary fluxes, and gradients along GHBs to encompass the range of transient fluctuations

# STEADY-STATE MODELING ASSUMPTIONS

- Average annual conditions represent the mean travel velocities and directions which are appropriate for evaluating migration and capture
- Furthermore, processing raw data at Red Hill indicates that flow directions are similar for 2006, 2015, and 2017 average annual conditions as for the 2006 synoptic study data
  - Fluctuations in water levels with time are generally similar at the Red Hill monitoring wells and water level differences result mainly due to local heterogeneities.

# STEADY-STATE MODELING ASSUMPTIONS

- Calibrating a transient model to long-term available data does not make a better model for our objectives
  - Sub-daily pumping variations are also averaged to time-scale of simulation
  - Water level measurements are sparse and not synoptic to pumping changes so tolerance / error / unknown / uncertainty is still large
  - Estimated recharge and pumping inputs can be varied during calibration to match all water level data points but achieves little in constraining the model
  - Of course there is uncertainty in raw data inputs – that is why it is not the signal but the noise (deviation from the underlying trend)
  - Transient simulation storage term buffers impacts making evaluations less conservative
  - Orders of magnitude more effort and provides less understanding and applicability

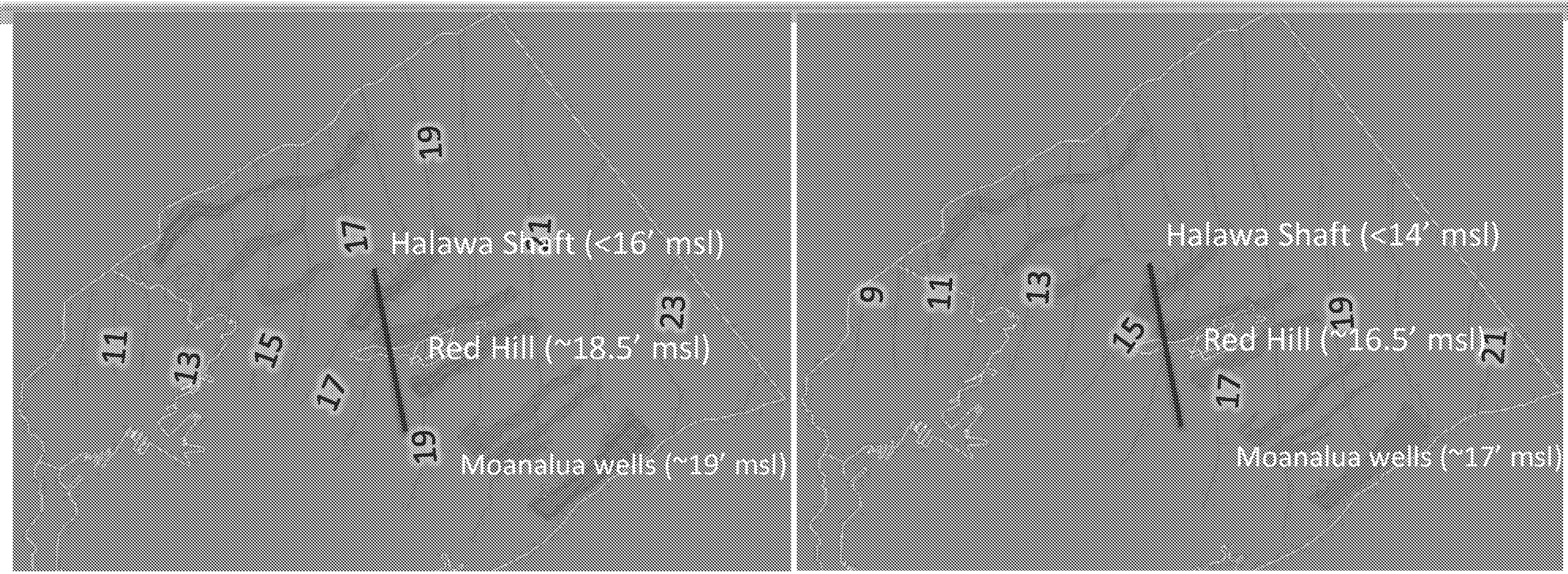
# HYDRAULIC GRADIENTS

From BWS letter dated 4/30/18:

Examination of the Figures reveals that groundwater levels in **Moanalua Valley** (represented by the Moanalua, DH43, and TAMC MW02 wells) are higher than levels at Red Hill Ridge (represented by OWDFMW01 ), which are **in turn higher than groundwater levels in Halawa Valley** (represented by Halawa Shaft, Halawa TZ, and Ka'amilo wells).

***This observed general pattern is contradicted by the Navy's interim groundwater model's predicted base case*** groundwater levels for model layer 2 on Slide 29.

# SLIDE 29 FROM APRIL 2018 GWFMWG MEETING: SENSITIVITY TO SAPROLITE PROPERTIES SAME AS BASALT – 2017 WATER LEVEL ELEVATIONS IN LAYER 2



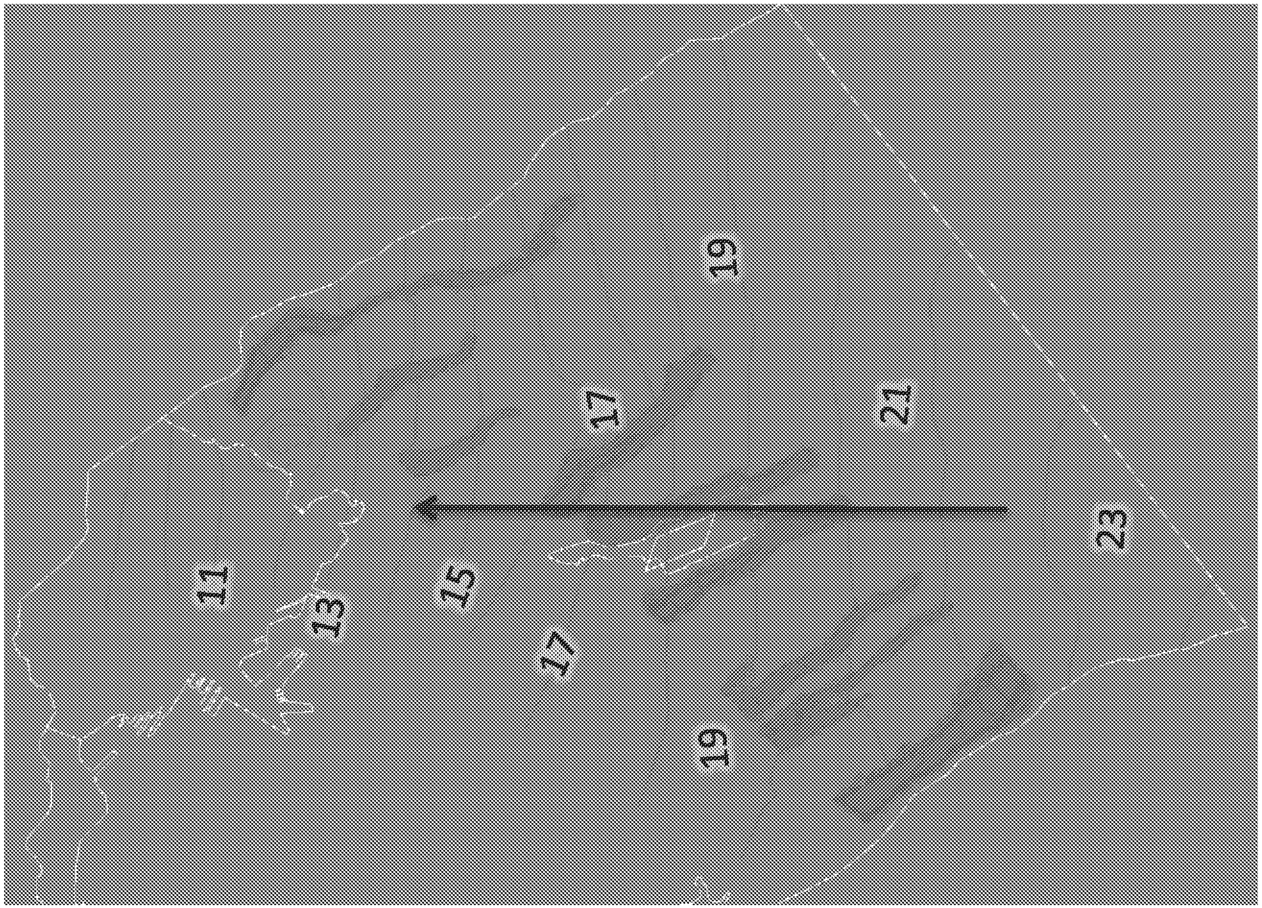

Base Case, 2017

Saprolite same as basalt, 2017

Key Observations:

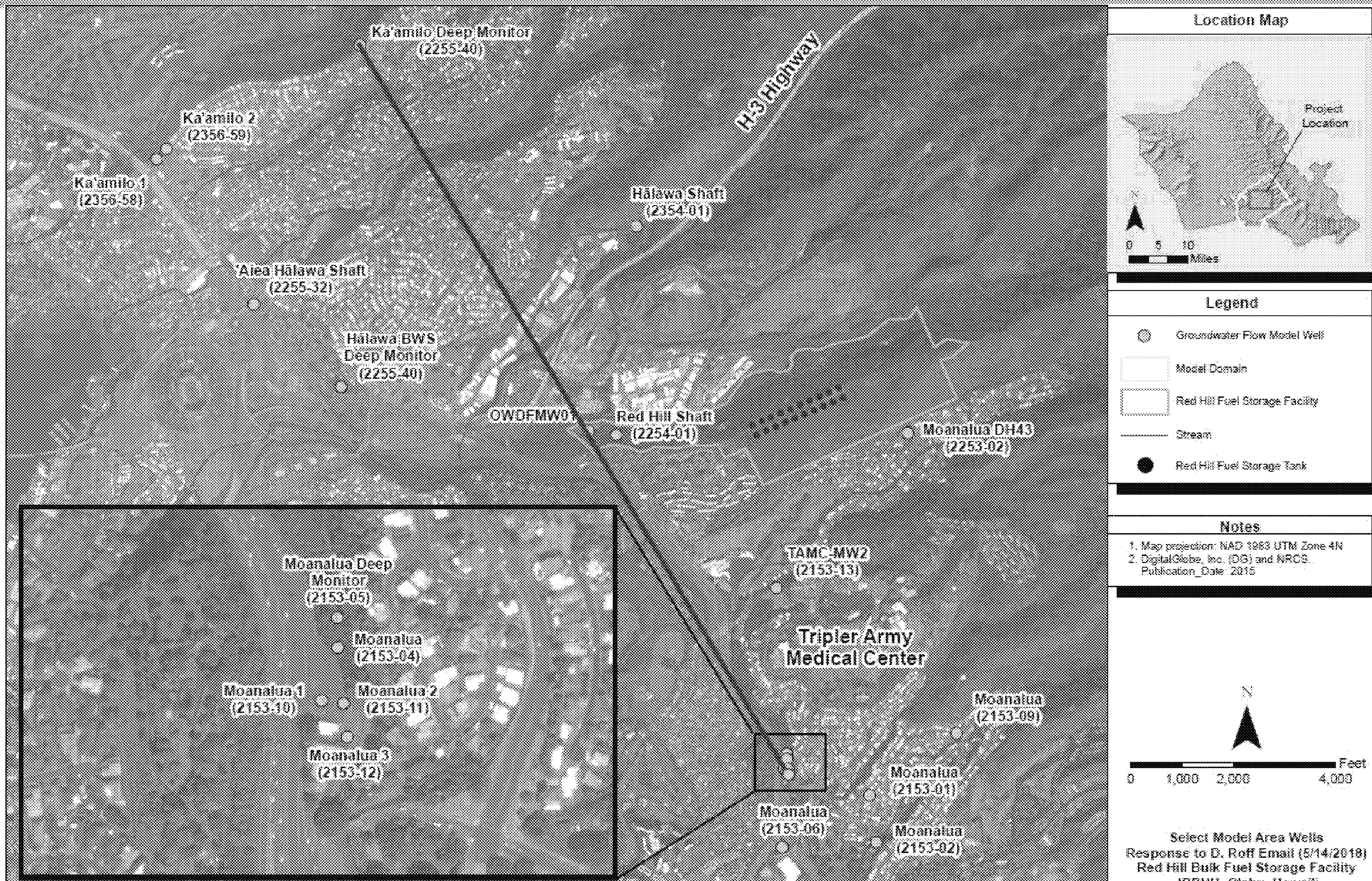
- No mounding within saprolite as in base case
- Water levels in basalt are lower than for base case by about 2 feet

# BUT WHAT IS THE DIRECTION OF THE HYDRAULIC GRADIENT?

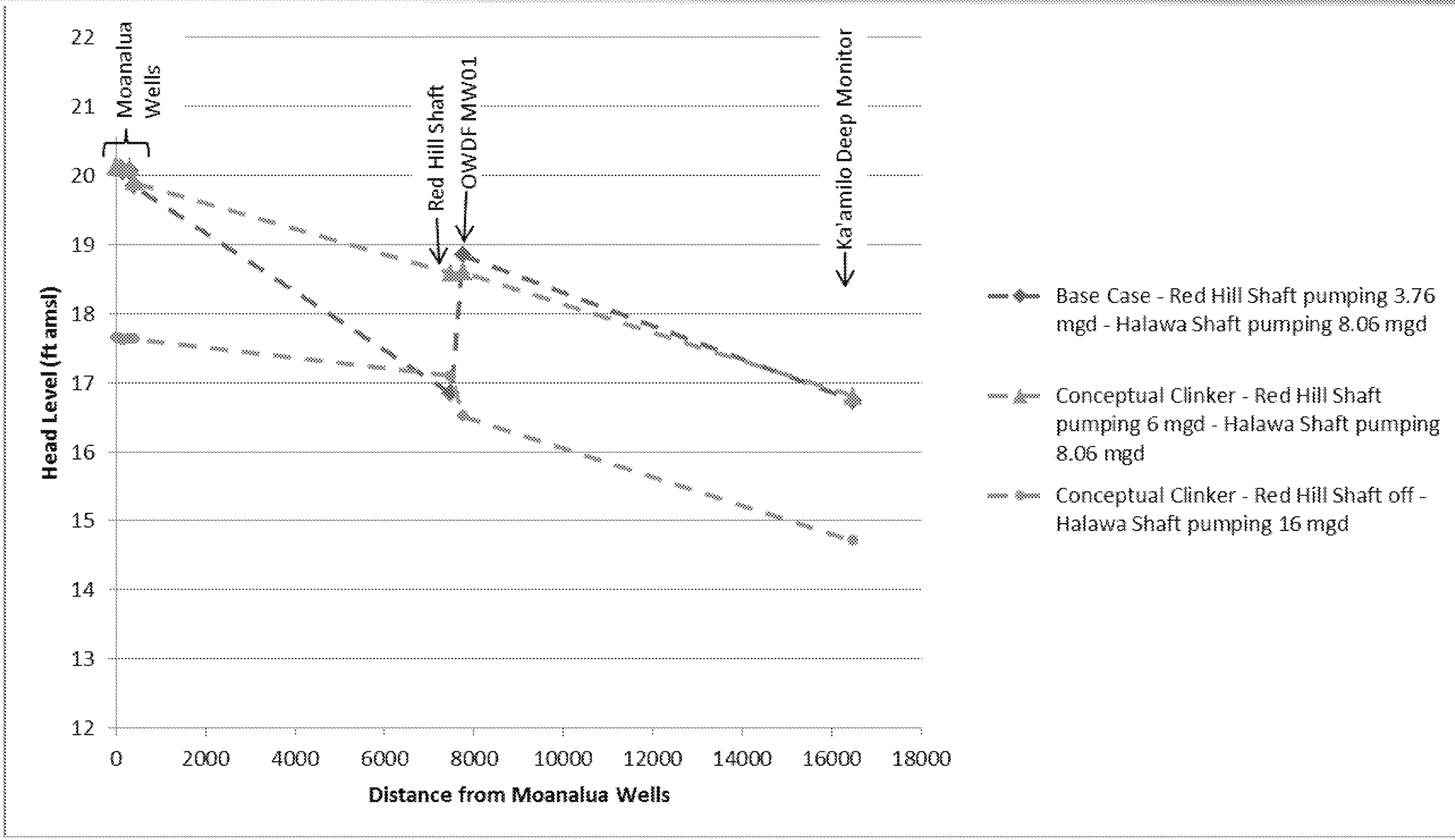



Simulated Hydraulic Gradient. But actual direction of flow is the resultant of the gradient and the preferential direction of hydraulic conductivity

# MOANALUA TO KA'AMILO DEEP TRANSECT

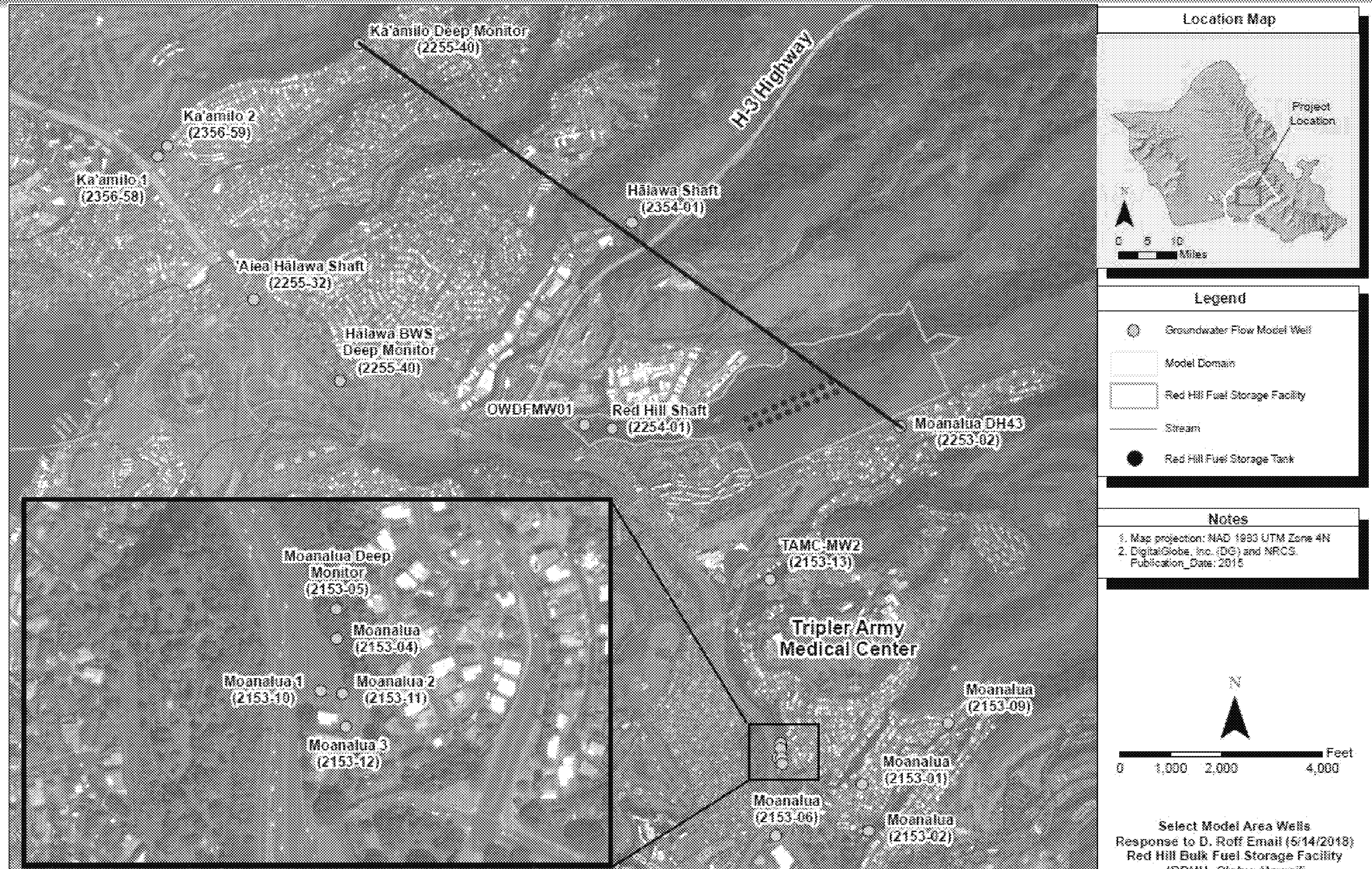


# WATER LEVELS FROM MOANALUA TO KA'AMILO DEEP

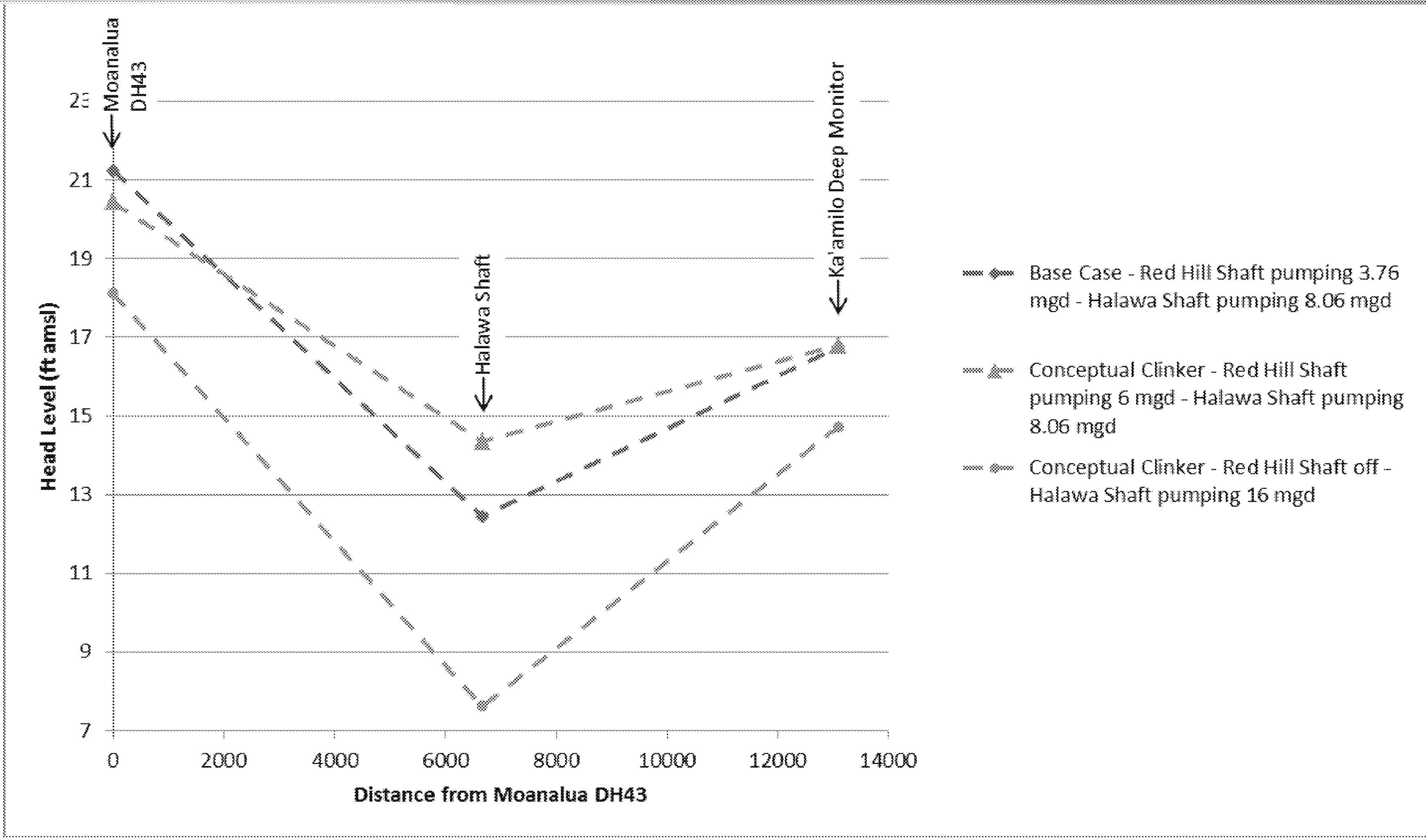



- **In general, groundwater head levels decrease from the southeast to the northwest**
- **However this transect is cross-gradient to the actual groundwater gradient**

# MOANALUA DH43 TO KA'AMILO DEEP TRANSECT



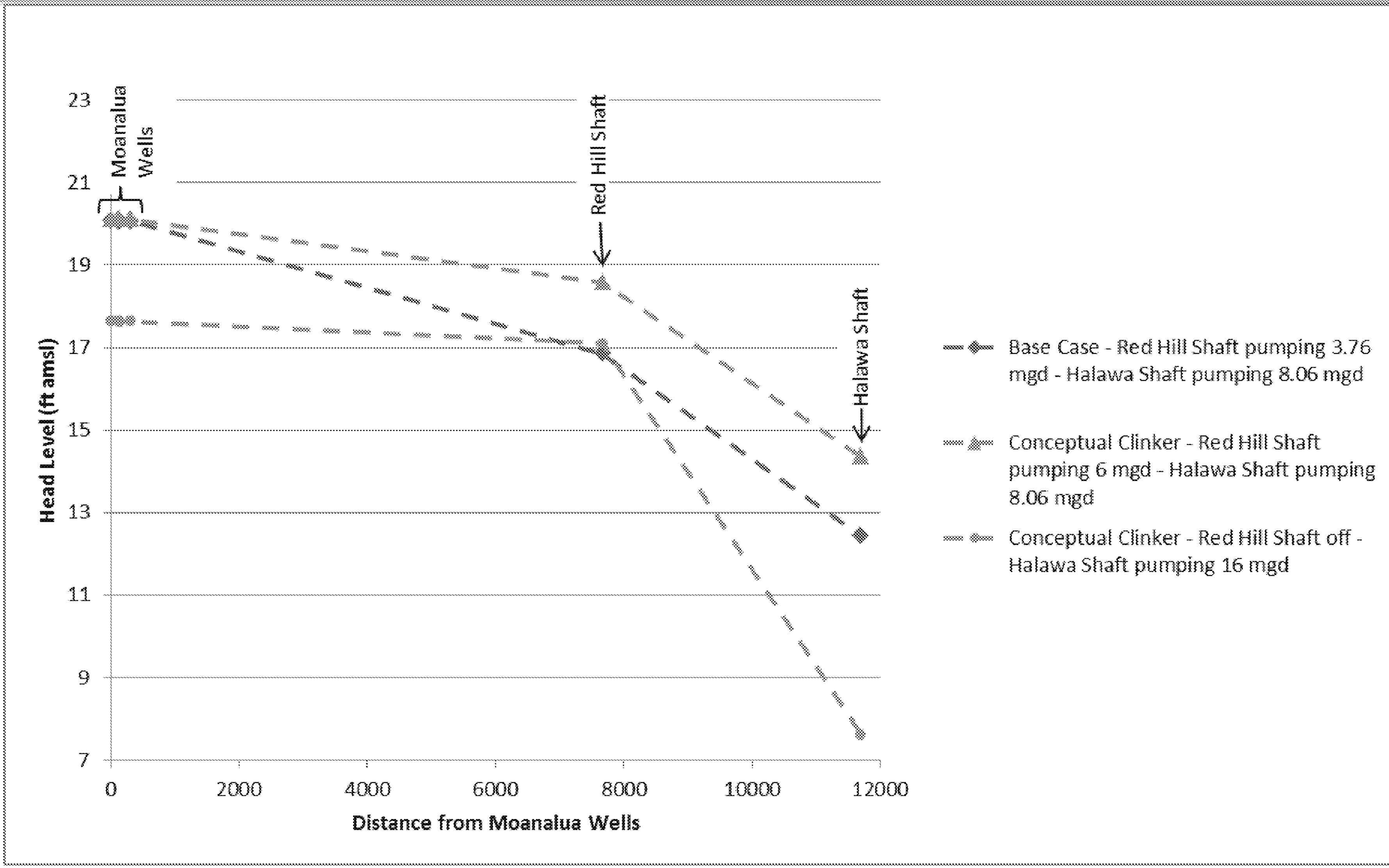
# WATER LEVELS FROM MOANALUA DH43 TO KA'AMILO DEEP



# SUMMARY OF WATER LEVELS FROM MOANALUA DH43 TO KA'AMILO DEEP

- Model shows head lower at Halawa Shaft than Moanalua DH43 and Ka'amilo Deep. **This is conservative for Halawa Shaft**.
- The groundwater gradient appears to be decreasing to the northwest, however this transect is cross-gradient
- Taking into consideration the regional groundwater levels, the groundwater gradient is generally from East to West, towards Pearl Harbor

# WATER LEVELS FROM MOANALUA TO HALAWA SHAFT



# FROM DOH PROVIDED AT APRIL 2018 GWFMWG MEETING

- Since the current groundwater model postulates a flow path that is generally consistent with the alignment of the monitoring well network we should see a significant decrease in groundwater elevation going toward Pearl Harbor (i.e. from RHMW04 to OWDFMW1).
  - Not necessarily significant, considering the high hydraulic conductivities of the clinker
  - Also, local heterogeneities could have impacts depending on whether the observation is in clinker, massive basalt, or saprolite

# ISSUES AND ACTION ITEMS FROM PREVIOUS MEETING AND BWS COMMENTS

# CONSIDERATIONS OF LOCAL FLOW GRADIENTS WITHIN THE REGIONAL GROUNDWATER FLOW SYSTEM

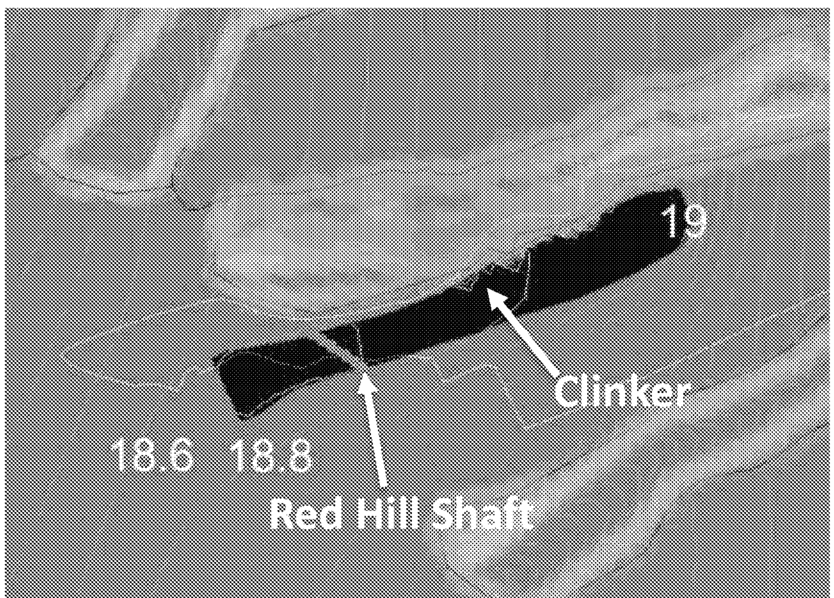
- Variations in local gradients are expected, especially in this type of geologic environment (high hydraulic conductivities and extremely flat gradient) due to local scale heterogeneities such as clinker zones, lava tubes and saprolite
  - Flat water table causes very small gradients. Data may be less accurate than the precision implies (precision of monitoring = 0.01 feet)
- Multiple models have been developed to evaluate impact of local scale heterogeneities
  - A model that includes conceptual sensitivity to presence of a clinker zone exhibits local flow gradients to the northwest and is less conservative for evaluation of flow towards Halawa Shaft
- Other modelers (Oki, SWAP, DON) have successfully used homogeneous anisotropic properties to model the basalt on a similar scale as the current application

# FROM DOH PROVIDED AT APRIL 2018 GWFMWG MEETING

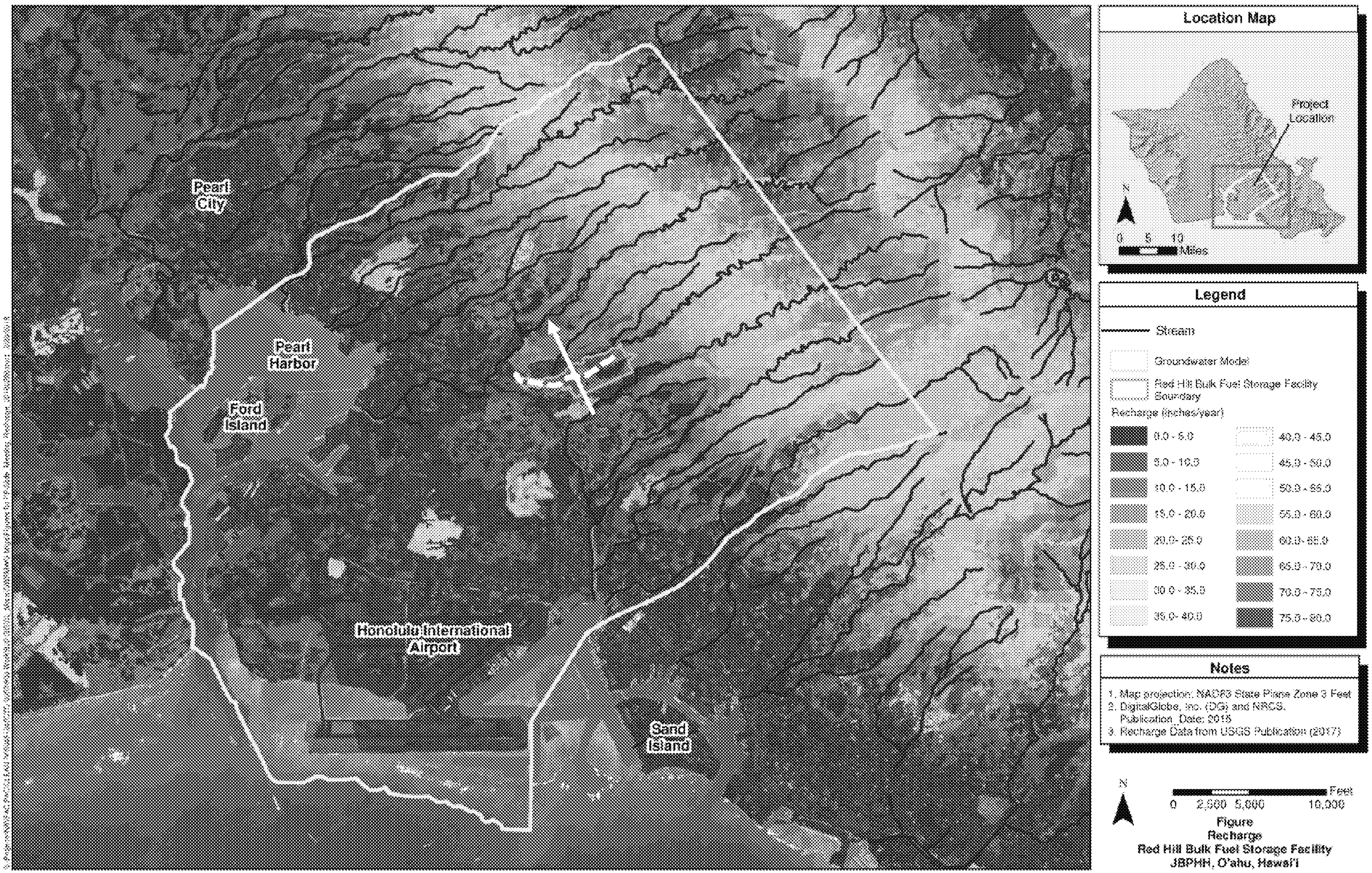
- ...there is implied flow direction toward the Halawa Shaft. The more salient point is that the data support a groundwater flow direction that is 90˚ offset from that which is currently postulated by the Navy.
  - The regional flow direction is postulated to be from mountain to sea, as well as all other previous conceptual models that cover the area
  - A clinker zone conceptualized to run along Red Hill ridge to Red Hill Shaft does postulate local flow towards the clinker material which is 90˚ offset from the regional flow direction
  - A sensitivity model that includes this clinker zone does simulate this local flow towards the clinker material which is 90˚ offset from the regional flow direction

# NW GRADIENTS DISCREPANCY

- Regional:
  - Model evaluations show consistency with measured water level differences when observed and simulated conditions are evaluated in a consistent manner with the base case and other sensitivity models
- Local over Red Hill:
  - Conceptual model includes a high transmissivity clinker zone between Red Hill and Red Hill Shaft identified by flat gradients between MW6 and MW8 and high production at the end of Red Hill Shaft outside of the basalt
  - Base case model does not include this heterogeneity to be protective of Halawa Shaft
  - Sensitivity model to conceptualization of clinker does indicate local NW gradients



# REGIONAL FLOW CONCEPTUALIZATION ?



# CHANGES FOR DECEMBER 2018 FLOW MODEL

1) Evaluate water level data for long-term trends and seasonal fluctuations using all data and all survey corrections
2) Evaluate water levels at pumping shafts from pumping drawdown characteristics at the shafts
3) Recompute calibration targets for 2006, 2015, and 2017
4) Evaluate latest geologic information to include saprolite depth at RHMW-11 and associated conceptualization
5) Include information on Honolulu Volcanics as another material zone in numerical model in all model layers as per current geologic interpretation
6) Include 2 zones in caprock to delineate low conductivity sediments in upland areas and marine sediments towards the coast
7) Include saltwater interface (model bottom elevation) from SUTRA model results. Interface computed by Gybhen-Herzberg Principle is okay under Red Hill but shallow as compared to SUTRA results under caprock, due to the vertical equilibrium assumption that may not be valid in caprock resulting from high vertical gradients therein

# CHANGES FOR DECEMBER 2018 FLOW MODEL

8) Redo vertical gridding to include 1 or 2 additional model layers near the water table for finer resolution of vertical gradients and transport concentrations. Saturated layer thickness of 20 feet for layers 2 and 3 under Red Hill, and expanding thickness further down is anticipated
9) Include corrected depths and geometries for water supply shafts
10) QA pumping rates and screen top and bottom elevations of pumping wells
11) Remove all wells that are outside of the domain, from the conceptual model wells. This is also confusing the water budgets since they are there in the conceptual model but not there in the numerical model
12) Develop a base-case groundwater flow model and simulate 2006, 2015, and 2017 steady-state conditions
13) Simulate transient flow conditions for synoptic studies of 2006, 2015, and 2017 with base case model
14) Develop sensitivity models to evaluate the impact of uncertainty in various parameters on the 2006, 2015, and 2017 steady-state flow conditions

# CHANGES FOR DECEMBER 2018 FLOW MODEL

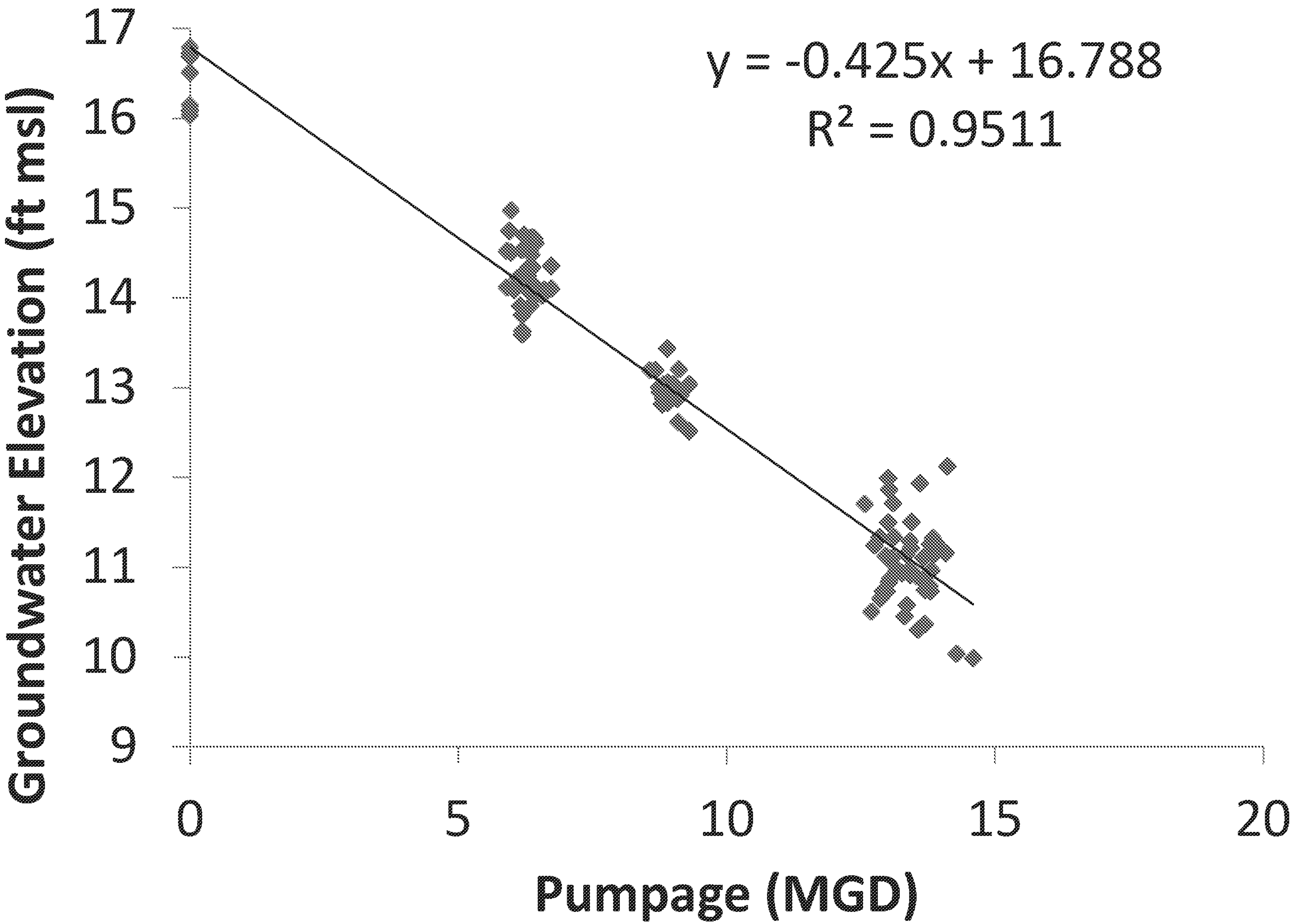
15) **Develop sensitivity models for transient synoptic studies of 2006, 2015, and 2017 to evaluate impact of uncertainty in various parameters on the transient flow responses**
16) **Simulate particle tracking from Red Hill Storage Facility area, and reverse tracking from water supply shafts for various scenarios to evaluate zones of influence for base-case and for sensitivity models**
17) **Develop solute transport models - one base-case model and other sensitivity models to evaluate impacts of uncertainties**
18) **Apply base-case solute transport models to evaluate various scenarios**
19) **Simulate critical scenarios with sensitivity models to evaluate impacts of uncertainties**

**The December 2018 Flow model updates have also been evaluated as sensitivity models for the interim modeling effort and demonstrate that it is appropriately conservative.**

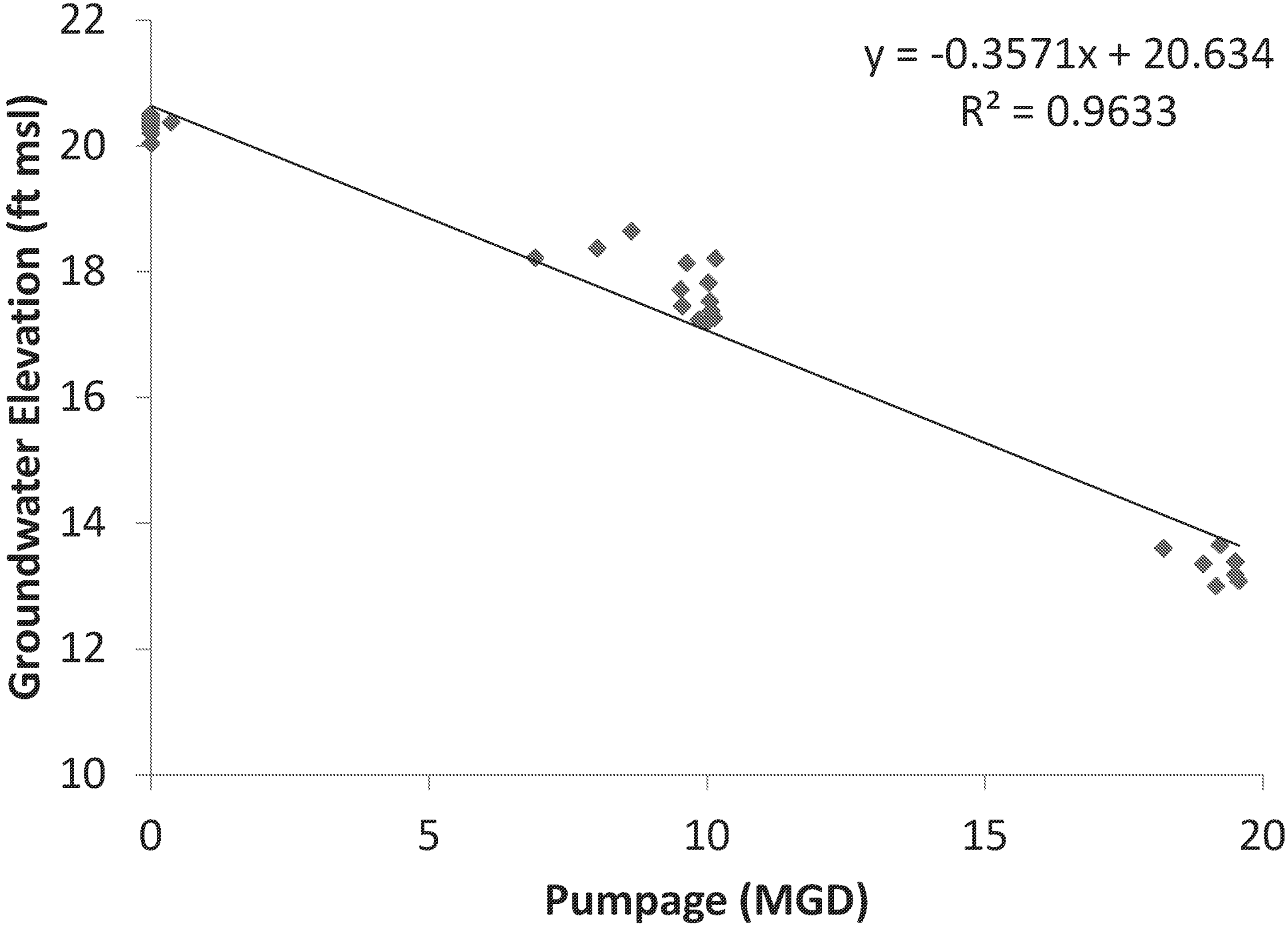
# IMPACT OF WITHDRAWALS ON WATER LEVELS IN PUMPING WELLS – FILTERING OF CONCURRENT PUMPING AND WATER LEVEL DATA

- **For Halawa Shaft:**
  - Consider any sequential difference in flux of greater than 1 mgd as stable
  - Filter out pumping data not stable for over 60 minutes
- **For Red Hill Shaft:**
  - Consider any sequential difference in flux of greater than 1 mgd as stable
  - Filter out pumping data not stable for over 60 minutes
  - Filter out pumping data not stable for more than six consecutive measurements

# HALAWA SHAFT PUMPING VS WLE IN SHAFT



# RED HILL SHAFT PUMPING VS WLE IN SHAFT



# SUMMARY OF PUMPING VS WLE EVALUATIONS IN HALAWA SHAFT

- Previously available data
  - At hourly intervals from 05-01-2015 through 05-31-2015
  - 743 data points; $R^2$ = 0.98; *4.38 feet drawdown for 10 MGD of pumping*
- Current data
  - At 10 minute intervals from 04-15-2015 through 07-21-2015
  - 13945 data points; *4.22 feet drawdown for 10 MGD of pumping*
  - Filtered data 122 data points; $R^2$ = 0.95; *4.25 feet drawdown for 10 MGD of pumping*
- *Halawa Shaft shows a linear drawdown response to pumping of about 4.3 feet for 10 MGD withdrawal rate*

# SUMMARY OF PUMPING VS WLE EVALUATIONS IN RED HILL SHAFT

- **Previously available data**
  - As available for 2006 (2 data points), 2015 (16 data points), and 2017 (9 data points)
  - *~3.5 feet drawdown for 10 MGD of pumping*
- **Current data**
  - At hourly intervals from 05-10-2006 through 06-09-2006; monthly from Jan 2013 through March 2017
  - 768 data points; *2.96 feet drawdown for 10 MGD of pumping*
  - Filtered data 32 data points; $R^2$ = 0.96; *3.57 feet drawdown for 10 MGD of pumping*
- ***Red Hill Shaft shows a linear drawdown response to pumping of about 3.5 feet for 10 MGD withdrawal rate***

# EVALUATE LATERAL BOUNDARY FLUXES RELATIVE TO SENSITIVITY ANALYSES

# CONCEPTUAL GROUNDWATER BUDGET ESTIMATES – 2006, 2015, AND 2017

| Year | 2006 | 2015 | 2017 |
|---|---|---|---|
| **IN** | | | |
| Recharge | 43.11 | 42.40 | 30.30 |
| NE Inflow | 22.4 | 22.4 | 22.4 |
| NW Inflow | 0 | 0 | 0 |
| SE Inflow | 0 | 0 | 0 |
| **Total IN** | **65.51** | **64.8** | **52.7** |
| **OUT** | | | |
| Well discharge | 43.12 | 37.93 | 31.46 |
| Pearl Harbor Spring at Kalauao discharge | 12.12 | 9.56 | 11.81 |
| Kalauao Spring discharge | 0.328 | 0.224 | 0.315 |
| Seafloor discharge | 9.94 | 17.09 | 9.12 |
| **Total OUT** | **65.5** | **64.8** | **52.7** |

Observations:

- Spring flow (correlated with WLEs at Navy 'Aiea well) is lowest in 2015
- Recharge and pumping are lowest in 2017

# BASE-CASE MODEL SIMULATED GROUNDWATER VOLUMETRIC BUDGET (MGD)

| Year | 2006 | 2015 | 2017 |
|---|---|---|---|
| **IN** | | | |
| NE Flux | 22.4 | 22.4 | 22.4 |
| Recharge | 48.0 | 35.8 | 36.8 |
| GHB Pearl Harbor Bay | 0.0 | 0.0 | 0.0 |
| GHB South | 0.0 | 0.0 | 0.0 |
| GHB NW Boundary | 0.0 | 0.0 | 0.0 |
| GHB SE Boundary | 0.0 | 0.0 | 0.0 |
| **Total IN** | **70.4** | **58.2** | **59.1** |
| **OUT** | | | |
| WELL Discharge | 37.4 | 28.0 | 26.8 |
| GHB Pearl Harbor Bay | 14.2 | 13.1 | 13.5 |
| Pearl Harbor Spring | 10.9 | 10.0 | 11.6 |
| Kalauao Spring | 0.1 | 0.1 | 0.1 |
| GHB Offshore | 8.1 | 7.2 | 7.3 |
| GHB NW Boundary | 0.0 | 0.0 | 0.0 |
| GHB SE Boundary | 0.0 | 0.0 | 0.0 |
| **Total OUT** | **70.7** | **58.4** | **59.4** |

Simulated water budget terms generally match conceptual model values

# CAPROCK ZONATION MODEL SIMULATED GROUNDWATER VOLUMETRIC BUDGET (MGD)

| Year | 2006 | 2015 | 2017 |
|---|---|---|---|
| **IN** | | | |
| NE Flux | 22.4 | 22.4 | 22.4 |
| Recharge | 48.0 | 35.8 | 36.8 |
| GHB Pearl Harbor Bay | 1.2 | 1.2 | 1.2 |
| GHB South | 0.0 | 0.0 | 0.0 |
| GHB NW Boundary | 115.6 | 117.2 | 115.1 |
| GHB SE Boundary | 0.0 | 0.0 | 0.0 |
| Total IN | 187.2 | 176.5 | 175.4 |
| **OUT** | | | |
| WELL Discharge | 37.1 | 28.7 | 26.9 |
| GHB Pearl Harbor Bay | 59.7 | 59.3 | 59.5 |
| Pearl Harbor Spring | 11.9 | 12.0 | 12.2 |
| Kalauao Spring | 0.2 | 0.2 | 0.2 |
| GHB Offshore | 30.3 | 29.5 | 29.6 |
| GHB NW Boundary | 48.0 | 46.8 | 47.0 |
| GHB SE Boundary | 0.0 | 0.0 | 0.0 |
| **Total OUT** | **187.2** | **176.5** | **175.4** |

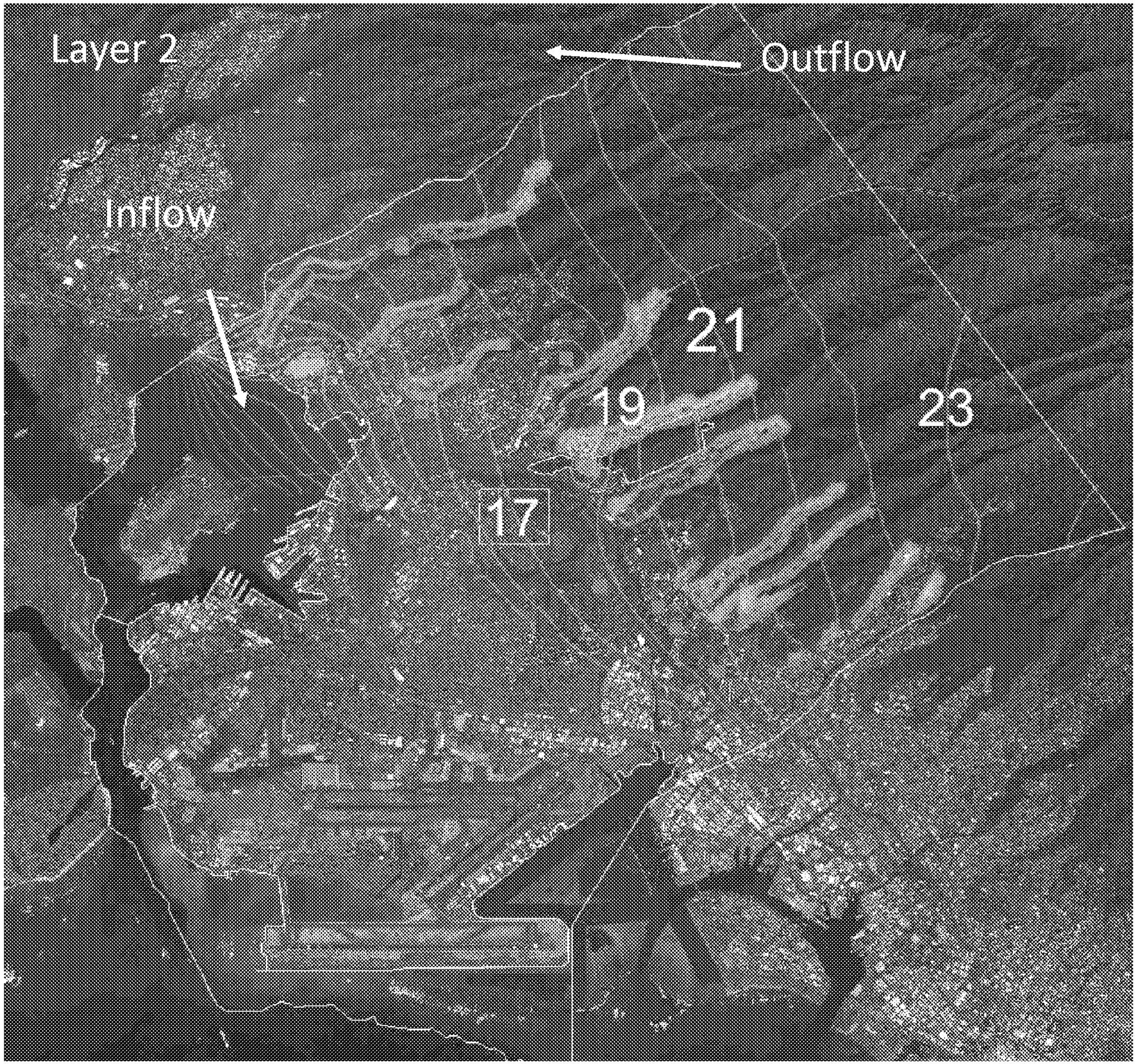
Large inflow from NE boundary with associated large outflows along into Pearl Harbor Bay, and in offshore areas

# CAPROCK ZONATION MODEL WITH SAPROLITE PROPERTIES SAME AS BASALT SIMULATED GROUNDWATER VOLUMETRIC BUDGET (MGD)

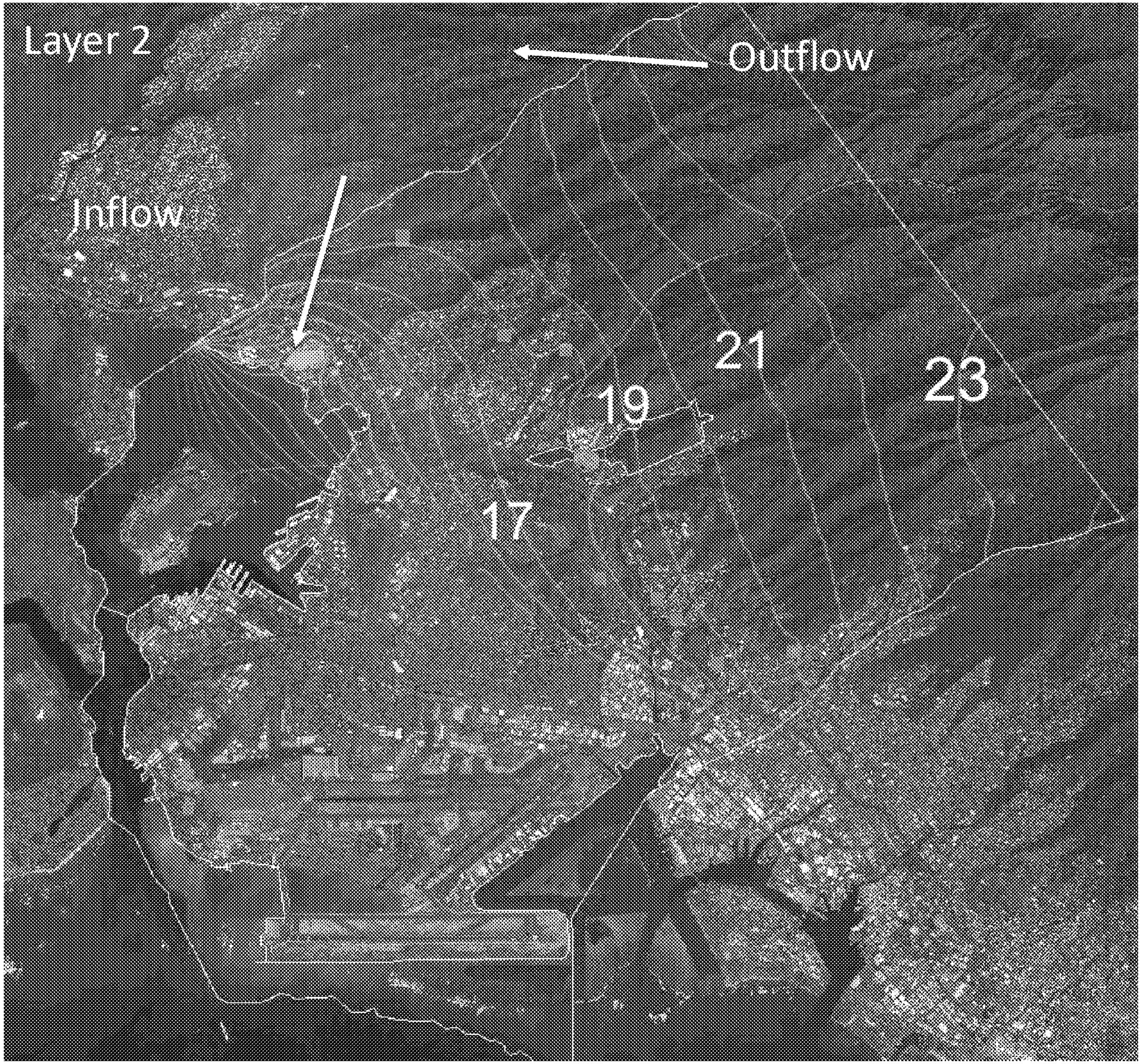
| Year | 2006 | 2015 | 2017 |
|---|---|---|---|
| **IN** | MGD | MGD | MGD |
| NE Flux | 22.4 | 22.4 | 22.4 |
| Recharge | 48.0 | 35.8 | 36.8 |
| GHB Pearl Harbor Bay | 1.2 | 1.2 | 1.2 |
| GHB South | 0.0 | 0.0 | 0.0 |
| GHB NW Boundary | 118.3 | 119.8 | 117.7 |
| GHB SE Boundary | 0.0 | 0.0 | 0.0 |
| **Total IN** | **189.9** | **179.2** | **178.0** |
| **OUT** | | | |
| WELL Discharge | 37.2 | 28.7 | 27.0 |
| GHB Pearl Harbor Bay | 60.3 | 59.9 | 60.1 |
| Pearl Harbor Spring | 12.7 | 12.8 | 13.0 |
| Kalauao Spring | 0.2 | 0.2 | 0.2 |
| GHB Offshore | 30.4 | 29.6 | 29.7 |
| GHB NW Boundary | 49.1 | 47.9 | 48.0 |
| GHB SE Boundary | 0.0 | 0.0 | 0.0 |
| **Total OUT** | **189.9** | **179.2** | **178.0** |

Similar budget terms as for case with saprolite

# CAPROCK ZONATION MODEL SIMULATED 2017 GROUNDWATER LEVELS OF LAYER 2



# CAPROCK ZONATION MODEL WITH SAPROLITE PROPERTIES SAME AS BASALT SIMULATED 2017 GROUNDWATER LEVELS OF LAYER 2



# INTERIM MODEL CONSERVATIVE ASSUMPTIONS

## Model Development

- Multiple models to evaluate the impact of uncertainty
  - The base case model does not include a high conductivity clinker zone that is conceptualized to occur between Red Hill and Red Hill Shaft that creates a potential short-circuit to Red Hill Shaft. Therefore, this base-case model is protective of Halawa Shaft.
  - A conceptual model including the clinker was also simulated and this model is protective of Red Hill Shaft.
  - Other models evaluate impacts of boundary fluxes/head values, stresses, and parameter uncertainty

# INTERIM MODEL CONSERVATIVE ASSUMPTIONS

## Model Calibration

- Regionally, the calibrated water levels are generally lower than measured in the northwest of the domain causing higher gradients towards the northwest than measured conditions. Therefore, the model is being protective of Halawa Shaft.
- Parameters for the models were evaluated with transient calibration runs against synoptic study data from 2006 and 2015. Observed behavior was bracketed by simulated results from the models.
- Various models were examined as sensitivities from the base-case to analyze the impact of parameter uncertainty on calibration. The various models were also evaluated as separate calibration-constrained models when possible, to assess if the recalibrated model is feasible, and to estimate particle migration using the various re-calibrated models.
- In most models, water levels at Halawa Shaft were simulated lower than measured relative to water levels at Red Hill Shaft causing larger draw towards Halawa Shaft as compared to the calibration dataset values

# INTERIM MODEL CONSERVATIVE ASSUMPTIONS

## Model Application

- Migration from the water table at Red Hill Storage Facility area and the influence zones of Red Hill Shaft and Halawa Shaft were simulated using two cases of extreme pumping conditions.
  - The first case analyzed impact of average pumping at Red Hill Shaft (3.76 mgd) and maximum pumping at Halawa Shaft (16 mgd) for an indefinite period, to evaluate capture at Red Hill Shaft.
  - The second case analyzed impact of zero pumping at Red Hill Shaft (0 mgd) and maximum pumping at Halawa Shaft (16 mgd) indefinitely. Both cases are extreme and not feasible currently.
- The models have been applied using a steady-state flow field of these extreme pumping conditions to note migration directions and times.
- Migration times were significantly larger than fluctuations in pumping at Red Hill Shaft or Halawa Shaft thus indicating that the average conditions of a steady-state flow-field are applicable over the duration of migration towards these shafts.

# SUMMARY OF THE SENSITIVITY ANALYSES/MULTIPLE MODELS TO EVALUATE THE IMPACT OF UNCERTAINTY

# SENSITIVITY ANALYSES

| Date Presented | Sensitivity model description | Base Case Value | Minimum Range | Maximum Range |
|---|---|---|---|---|
| 2/12/2018 | Sensitivity to vertical hydraulic conductivity of basalt | 20 | 2 ft/d | 200 ft/d |
| | Sensitivity to conductance of offshore general head boundaries | | | |
| | Pearl Harbor | 0.005 | 0.0005 1/d | 0.05 1/d |
| | Offshore | 0.014 | 0.0014 1/d | 0.14 1/d |
| | Sensitivity to recharge (* 0.8 and * 1.2) | | | |
| | 2006 | 48.04 | 40.03 mgd | 57.65 mgd |
| | 2015 | 35.81 | 29.84 mgd | 42.97 mgd |
| | 2017 | 36.77 | 30.64 mgd | 44.12 mgd |
| | Sensitivity to saprolite hydraulic conductivity | | | |
| | Layer 2 Kh | 0.1 | 0.01 ft/d | 1 ft/d |
| | Layer 2 Kv | 0.01 | 0.001 ft/d | 0.1 ft/d |
| | Layer 3 Kh | 10 | 1 ft/d | 100 ft/d |
| | Layer 3 Kv | 1 | 0.1 ft/d | 10 ft/d |
| | Sensitivity to basalt horiontal anisotropy | 0.33 | 0.2 | 0.5 |
| | Sensitivity to NW flux (* 0.8 and * 1.2) | 22.4 | 17.9 mgd | 26.9 mgd |
| | Sensitivity to horizontal hydraulic conductivity of caprock | 1,204 | 100 ft/d | 2,400 ft/d |

# SENSITIVITY ANALYSES

| Date Presented | Sensitivity model description | Base Case Value | Minimum Range | Maximum Range |
|---|---|---|---|---|
| 3/16/2018 | Sensitivity to heterogeneity: presence of clinker (K=500,000 ft/d) at water table under Red Hill | Conceptual | | |
| | Sensitivity to influence of GHB stage along NW and SE boundaries (1) | High GHB Conductance, Stage as per interpolated values | | |
| | Sensitivity to influence of GHB stage along NW and SE boundaries (2) | Larger head drop from mountain to shore on GHBs | | |
| | Sensitivity to influence of GHB stage along NW and SE boundaries (3) | More northwestern gradients on GHBs | | |
| | Sensitivity to influence of GHB stage along NW and SE boundaries (4) | Smaller head drop from mountain to shore on GHBs | | |
| | Sensitivity to saprolite properties same as basalt | Conceptually no saprolite present in domain | | |
| | Sensitivity to lower vertical hydraulic conductivity of basalt with higher hydraulic conductivity for saprolite | Two parameter change requested | | |
| | Sensitivity to horiontal hydraulic conductivity of basalt | 2,000 | | 6,000 ft/d |
| | **Sensitivity analysis to transient synoptic studies of 2006** | | | |
| | Specific yield *0.1 | | | |
| | Specific yield *10 | | | |
| | Specific Storage * 0.1 | | | |
| | Specific Storage * 10 | | | |
| | with low anisotropy of 0.2 | | | |
| | with high anisotropy of 0.5 | | | |
| | with saprolite properties same as basalt | | | |
| | with presence of clinker | | | |
| | with basalt hydraulic conductivity = 6,000 ft/d | | | |

# SENSITIVITY ANALYSES

| Date Presented | Sensitivity model description | Base Case Value | Minimum Range | Maximum Range |
|---|---|---|---|---|
| 4/13/2018 | Sensitivity to horizontal hydraulic conductivity of caprok being as low as 1 ft/d | 1,204 | 1 ft/d | |
| | Sensitivity to influence of GHB stage along NW boundary (1B) | Adjusted (higher) GHB head in basalt near Pearl Harbor | | |
| | Sensitivity - incorporate Halawa shaft and Red Hill shaft as-builts into model | Use as-built drawings (previously used TEC model elevations) | | |
| | Sensitivity to rind of low hydraulic conductivity caprock | Conceptually categorize caprock into alluvial and marine sediments | | |
| | Sensitivity to saprolite properties same as basalt with rind of low hydraulic conductivity in caprock | | | |

# ADDRESSING UNCERTAINTY IN MODELING

- **Multiple models used to evaluate uncertainty in model parameters and conceptualization**
  - A total of 69 different sensitivity models including "what-if" scenarios to evaluate impact on conceptualization, calibration and migration / capture zones
- **Use of conservative models for evaluating various critical objectives**
  - Conceptual models protective of Red Hill Shaft include a clinker zone between Red Hill facility and the Red Hill Shaft
  - Conceptual models protective of Halawa Shaft do not include a clinker zone and evaluate high hydraulic conductivity of the saprolite barrier. Also includes a "what-if" condition of no saprolite barrier
- **Application of models for extreme operating conditions**
  - Red Hill Shaft pumping at average conditions (3.76 mgd) and Halawa Shaft pumping at maximum conditions (16 mgd) indefinitely
  - Red Hill Shaft not pumping and Halawa Shaft pumping at maximum conditions (16 mgd) indefinitely

# SYNOPTIC WATER LEVEL STUDY UPDATE

# SUMMARY AND NEXT STEPS